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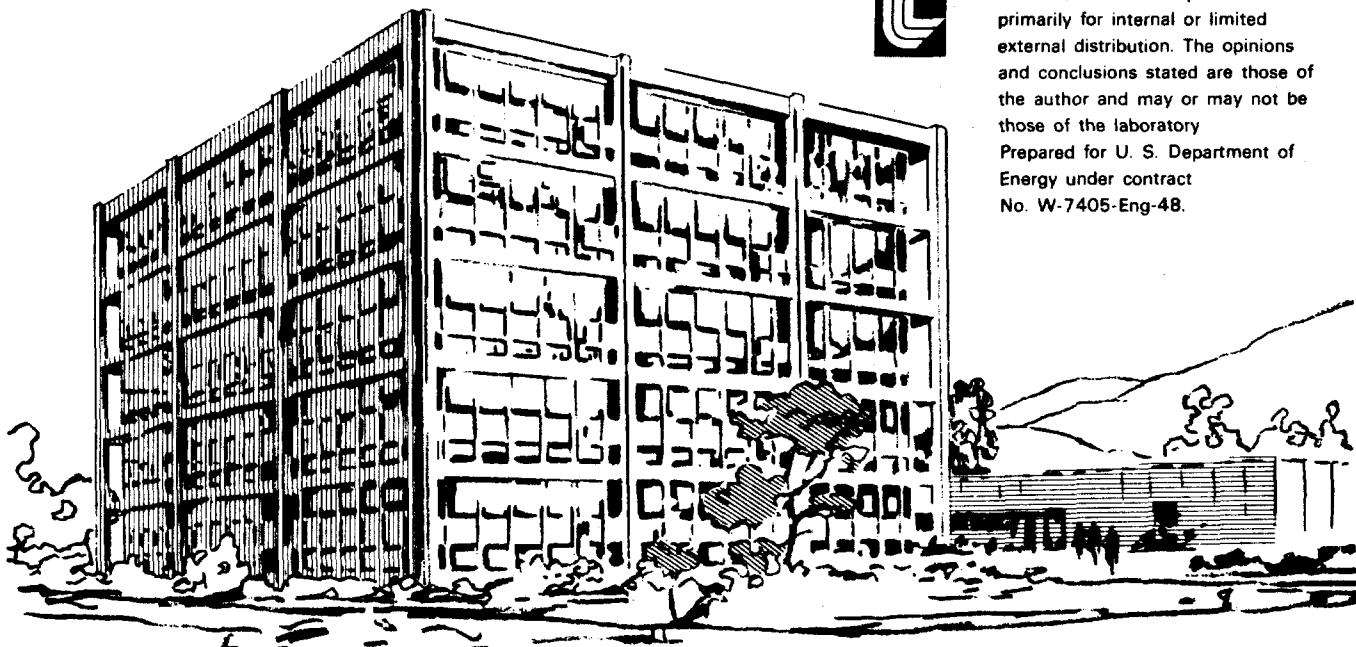
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FIBER COMPOSITE FLYWHEEL PROGRAM:
Filament-Wound Composite Data Sheets

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Abstract

In this report we present data sheets summarizing engineering design results we obtained for filament-wound composite materials that are suitable for flywheel applications. The composites include 60 vol% Kevlar 49 in two different epoxy matrices; 60, 65, and 70 vol% E glass in a room-temperature curable epoxy matrix; and 50, 55, 60, 65, and 70 vol% S-2 glass in the same room-temperature curable epoxy matrix. We present information on mechanical and thermal properties for the composites, including elastic constants, compliance components and invariants, and ultimates. We also include average stress-strain curves for tension, compression, and shear. The values given are for good quality filament-wound composites prepared by commercially feasible techniques.

Scope of Fiber Composites Study

Fiber composite flywheels are especially suitable for energy storage systems because they have high strength-to-density ratios, enabling them to store large amounts of kinetic energy per unit mass. At LLL we have an ongoing program of composites research, one objective of which is to provide data for flywheel designs. This report presents information obtained to date on 10 filament-wound composites that may be useful for design applications.

For convenience, the information is summarized on data sheets that list the fibers' mechanical and thermal properties, including elastic constants, compliance components and invariants, and ultimates. Also included are average stress-strain curves for tension, compression, and shear. The composites studied are 60 vol% Kevlar 49 in two different epoxy matrices; 60, 65, and 70 vol% E glass in a room-temperature curable epoxy matrix; and 50, 55, 60, 65, and 70 vol% S-2 glass in the same room-temperature curable epoxy matrix. Table 1 is an index to the data sheets which follow it.

Experimental Specifications

All the fibers used in the composites of this report are available commercially. Detailed properties for these and other fibers are given in manufacturers' and suppliers' data sheets summarized in Ref. 1. The epoxy resin matrices used have been characterized at LLL; their properties are summarized in the work cited in Ref. 2. In general, weight proportions of resin and curing agents were selected to give a stoichiometric ratio for each lot of resin.

The technical specifics of the filament winding and characterization of each composite have been reported elsewhere, as cited on the data sheets. For the mechanical tests, the American Society for Testing and Materials (ASTM) standard test procedures were used where applicable. Longitudinal tension (LT) tests were performed according to ASTM standard D3039-74 and D2290-76, modified to allow for the use of an elongated ring specimen. Both longitudinal compression (LC) and transverse compression (TC) tests followed ASTM standard D3410-75. Transverse tensile (TT) tests were performed according to ASTM standard D3039-74, and shear strain tests followed ASTM

standard D3518-76. Mechanical testing was done according to the appropriate procedure on a standard, constant crosshead-displacement, mechanical testing machine which is screw-driven and has a 10-Mg capacity. Bonded foil-resistance strain gauges were used to measure strain and hence, elastic constants. For most tests, the engineering strain rate was about 3×10^{-4} /s, except that a strain rate of 2.6×10^{-5} /s was used for the transverse tensile tests of E-glass composites. This variation was necessary because of their very low ultimate-failure strains. All specimens were conditioned at 23°C and 50 percent relative humidity for at least 24 hours prior to testing and were tested in this same environment. We obtained data by using a multi-channel digital system that recorded the test data on magnetic tape for later computer reduction and processing.

Data Analysis Procedures and Limitations

For longitudinal tests, fiber stress was determined from the rule of mixtures and the specimen fiber vol% which we measured. These data were then averaged for all specimens, and the stresses, compliance, and moduli at each vol% fiber were calculated from this single set of data using the rule of mixtures. The validity of this approach was confirmed over the range of volume percentages studied for each of the composites.

Composite elastic constants were calculated from the in-plane compliance tensor. The components of this tensor are given for each of the composites studied. Appendix 1 describes in detail the calculation of the elastic constants. For all of the composites studied, elastic constants and compliances are the same for tension and compression, in both longitudinal and transverse modes. We give data limits as 95 percent confidence limits.

In general, the vol% fiber shown on the composite data sheet is a nominal value; actual specimens varied from this value by ± 2.5 vol%. In some cases, the data are interpolated or extrapolated to the desired vol% fiber. Data that has been interpolated or extrapolated, that are only approximate for that vol% fiber, or that are questionable, are so noted. Extremely approximate or questionable data are shown in parentheses.

Performing compression tests is particularly difficult for fiber composites, and the range of error in those results is rather large. This testing problem is particularly severe for the Kelvar composites. Consequently, we show only limited compression testing results for most of the composites.

Values for properties of many composites are extremely process-dependent. This is especially true for all transverse-tensile ultimates, for longitudinal-tensile ultimates on glass composites, and for all thermal conductivity data. The values given in this report are for good quality filament-wound composites and the values were obtained without resorting to expensive or non-commercially feasible techniques. Poor quality or exceptionally high quality composites may give significantly different values of transverse and longitudinal ultimates and thermal conductivity from those reported here. The data of this report should, however, accurately represent filament-wound composites of good commercial quality.

Table 1. Index of filament-wound epoxy composite data sheets.

System	Vol%	Data Sheet No.
Kevlar 49/XD 7818-T403	60	1
Kevlar 49/DER 332-T403	60	2
E glass/DER 332-T403	60	3
E glass/DER 332-T403	65	4
E glass/DER 332-T403	70	5
S-2 glass/DER 332-T403	50	6
S-2 glass/DER 332-T403	55	7
S-2 glass/DER 332-T403	60	8
S-2 glass/DER 332-T403	65	9
S-2 glass/DER 332-T403	70	10

Filament-Wound Composite Data Sheet 1. 60 vol% Kevlar 49/XD 7818-T403 epoxy^{3,4}

Fiber: Kevlar 49, Type 968, 1420 denier from duPont
 Matrix: 100 parts Dow Chemical XD 7818 (bisphenol-F based epoxy resin), 49 parts Jefferson Chemical Jeffamine T-403 (polyether triamine)
 Cure: 16 h at 60°C or ~48 h at room temperature to gel, then 3 h at 90°C

Mechanical Properties

Elastic constants^a

Longitudinal Young's modulus (E_{11}), GPa	75.1 ± 3.0
Transverse Young's modulus (E_{22}), GPa	4.56 ± 0.23
Shear modulus (G_{12}), GPa	1.893 ± 0.027
Major Poisson's ratio (ν_{12})	0.406 ± 0.055
Minor Poisson's ratio (ν_{21})	0.0247 ± 0.0038

Ultimates	Tension	Compression	Shear
Longitudinal strength, MPa	1400 ± 200	235 ± 3	-
Longitudinal ultimate strain, %	1.7 ± 0.2	0.48 ± 0.3	-
Transverse strength, MPa	12.4 ± 0.4	53 ± 3	-
Transverse ultimate strain, %	0.283 ± 0.011	1.41 ± 0.12	-
Shear stress at 0.2% offset, MPa	-	-	33.67 ± 0.54
Shear strain at 0.2% offset, %	-	-	1.982 ± 0.034

Thermal Properties^b

	Temperature, °C							
	-50	-25	0	25	50	75	100	125
Linear coefficient of thermal expansion, ($10^{-6}/°C$)								
Longitudinal ^c	-3.8	-3.8	-3.8	-4.0	-4.7	-6.0	-	-
Transverse	50	50	54	60	73	~150	160	160
Thermal conductivity, (W/m·°C)								
Longitudinal ^c	2.62	2.84	3.05	3.22	3.31	3.34	-	-
Transverse	0.63	0.73	0.83	0.93	1.03	1.13		
Heat capacity, (J/kg·°C)	860	940	1030	1120	1200	2650	-	-

a. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

		<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01340 ± 0.00058	19
S_{12} , GPa ⁻¹	-0.00544 ± 0.00068	15
S_{22} , GPa ⁻¹	0.2203 ± 0.0113	12
S_{66} , GPa ⁻¹	0.5284 ± 0.0073	8

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

		<u>Minimum No. of specimens</u>
I_1 , GPa ⁻¹	0.2228 ± 0.0115	12
I_2 , GPa ⁻¹	0.5502 ± 0.0085	8
II_1 , GPa ⁻¹	0.1035 ± 0.0057	12
II_2 , GPa ⁻¹	0.0355 ± 0.0021	8

- b. Results taken from tests of one specimen only.
c. Estimated from results for Kevlar 49 in a DER 332-T403 epoxy matrix.

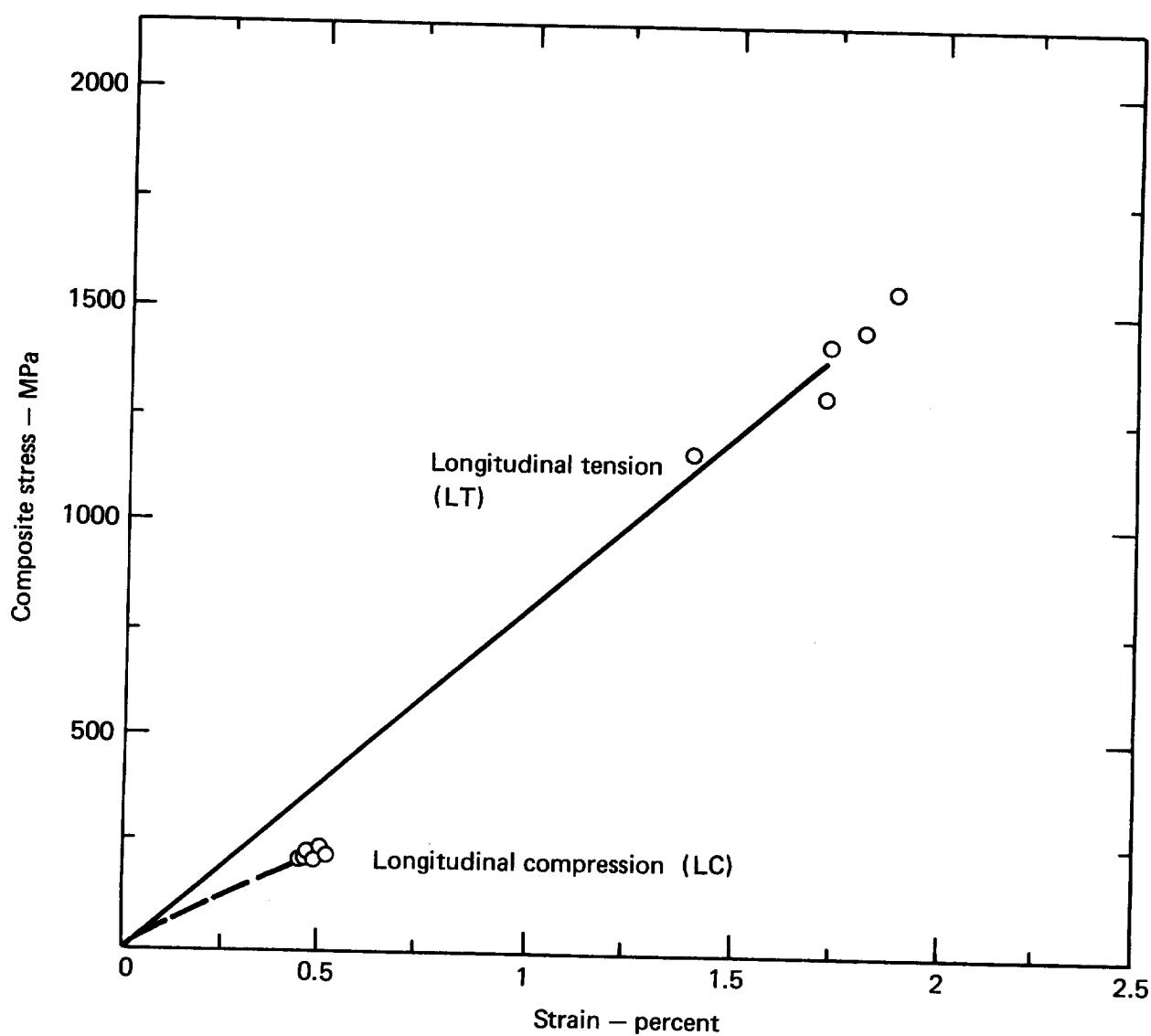


Fig. 1. Average longitudinal stress-strain, with individual failure points, for Kevlar 49 in XD 7818-T403 epoxy matrix. Stress values are normalized to 60 vol% fiber. Actual vol% fiber: 58-71(LT), 57.8(LC); No. of specimens: elastic constants, 15, ultimates, 5(LT), 6(LC).

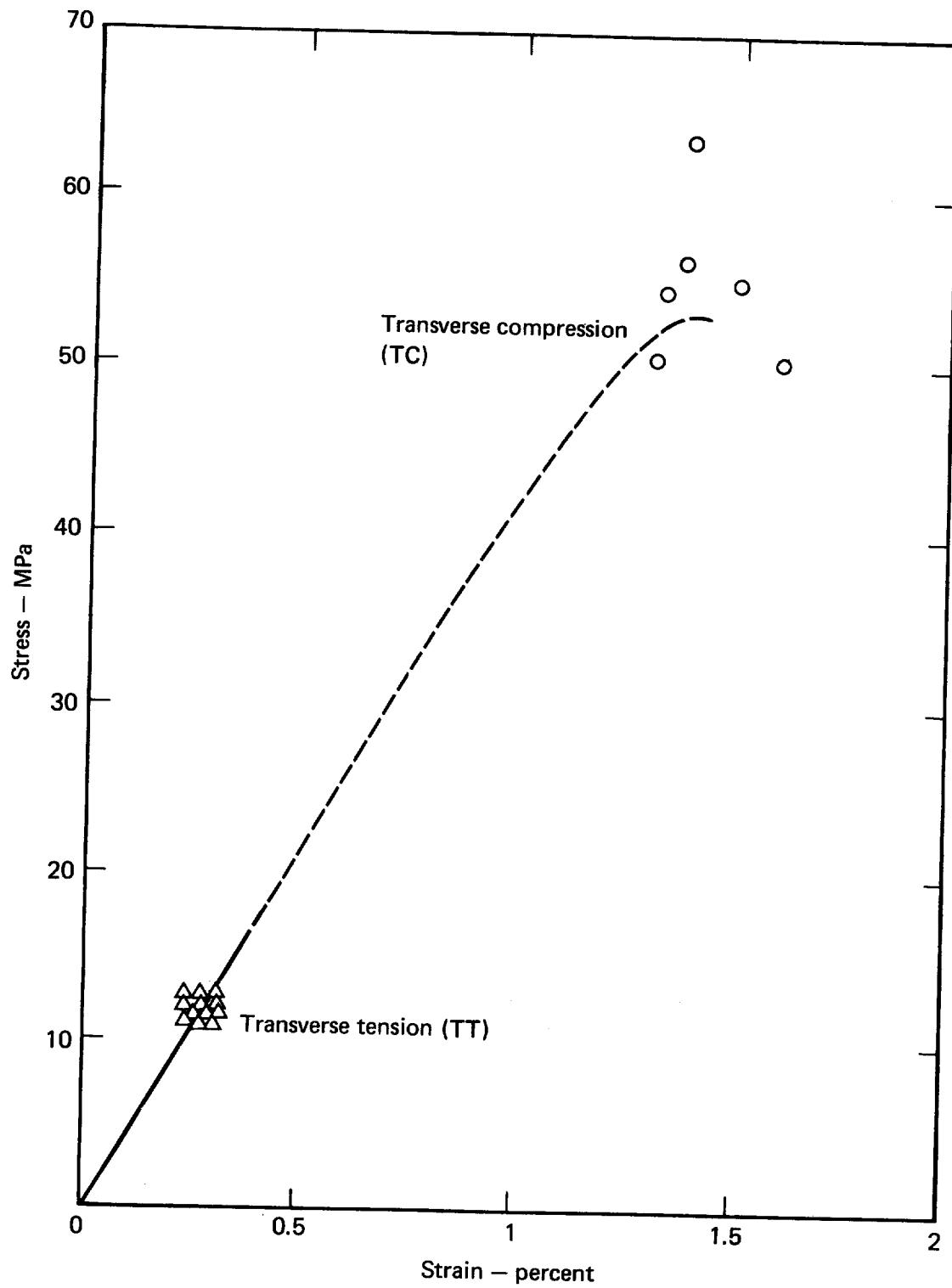


Fig. 2. Average transverse stress-strain, with individual failure points, for Kevlar 49 (nominally 60 vol%) in XD 7818-T403 epoxy matrix. Actual vol% fiber: 57-60(TT), 60.5(TC); No. of specimens: elastic constants, 12; stress, 11(TT), 10(TC); strain, 11(TT), 6(TC).

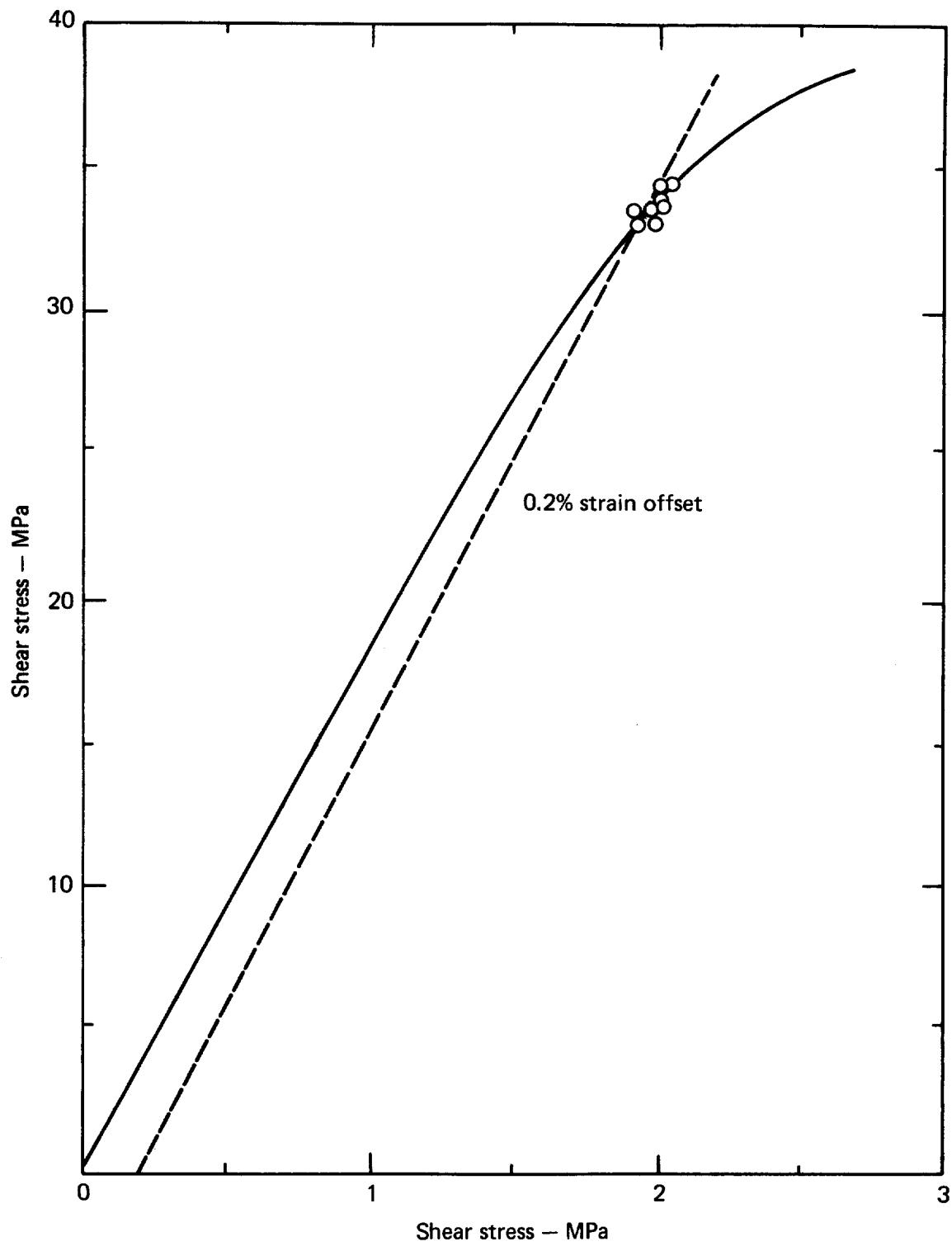


Fig. 3. Average shear stress-strain, with individual values at 0.2 percent strain offset, for Kevlar 49 (nominally 60 vol%) in XD 7818-T403 epoxy matrix. Actual vol% fiber: 58.3; No. of specimens: 8.

Filament-Wound Composite Data Sheet 2. 60 vol% Kevlar 49/DER 332-T403 epoxy⁴

Fiber: Kevlar 49, Type 968, 1420 denier from duPont
 Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A based epoxy resin), 45 parts Jefferson Chemical Jeffamine T-403 (polyether triamine)
 Cure: 1 d at room temperature and 16 h at 85°C.

Mechanical Properties

Elastic constants^a

Longitudinal Young's modulus (E_{11}), GPa	81.8 ± 1.5
Transverse Young's modulus (E_{22}), GPa	5.10 ± 0.10
Shear modulus (G_{12}), GPa	1.82 ± 0.09
Major Poisson's ratio (ν_{12})	0.310 ± 0.035
Minor Poisson's ratio (ν_{21})	0.0193 ± 0.0014

Ultimates	Tension	Compression	Shear
Longitudinal strength, MPa	1850 ± 50	235 ± 3^b	-
Longitudinal ultimate strain, %	2.23 ± 0.06	0.48 ± 0.3^b	-
Transverse strength, MPa	7.9 ± 1.1	53 ± 3^b	-
Transverse ultimate strain, %	0.161 ± 0.023	1.41 ± 0.12^b	-
Shear stress at 0.2% offset, MPa	-	-	24.4 ± 2.4
Shear strain at 0.2% offset, %	-	-	1.55 ± 0.16

Thermal Properties^c

	Temperature, °C							
	-50	-25	0	25	50	75	100	125
Linear coefficient of thermal expansion, ($10^{-6}/°C$)								
Longitudinal	-3.8	-3.8	-3.8	-4.0	-4.7	-6.0	-	-
Transverse	61	66	72	79	87	150	214	214
Thermal conductivity, (W/m·°C)								
Longitudinal	2.62	2.84	3.05	3.22	3.31	3.34	-	-
Transverse	-	0.27	0.33	0.35	0.37	0.39	-	-
Heat capacity, (J/kg·°C)	840	930	1020	1120	1190	1300	-	-

a. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

		<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01222 ± 0.00023	5
S_{12} , GPa ⁻¹	-0.00379 ± 0.00023	10
S_{22} , GPa ⁻¹	0.1961 ± 0.0039	8
S_{66} , GPa ⁻¹	0.549 ± 0.026	5

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

		<u>Minimum No. of specimens</u>
I_1 , GPa ⁻¹	0.201 ± 0.006	5
I_2 , GPa ⁻¹	0.564 ± 0.026	5
II_1 , GPa ⁻¹	0.0920 ± 0.0030	5
II_2 , GPa ⁻¹	0.0416 ± 0.0034	5

- b. Estimated from results for Kevlar 49 in an XD 7818-T403 epoxy matrix.
c. Results taken from tests of one specimen only.

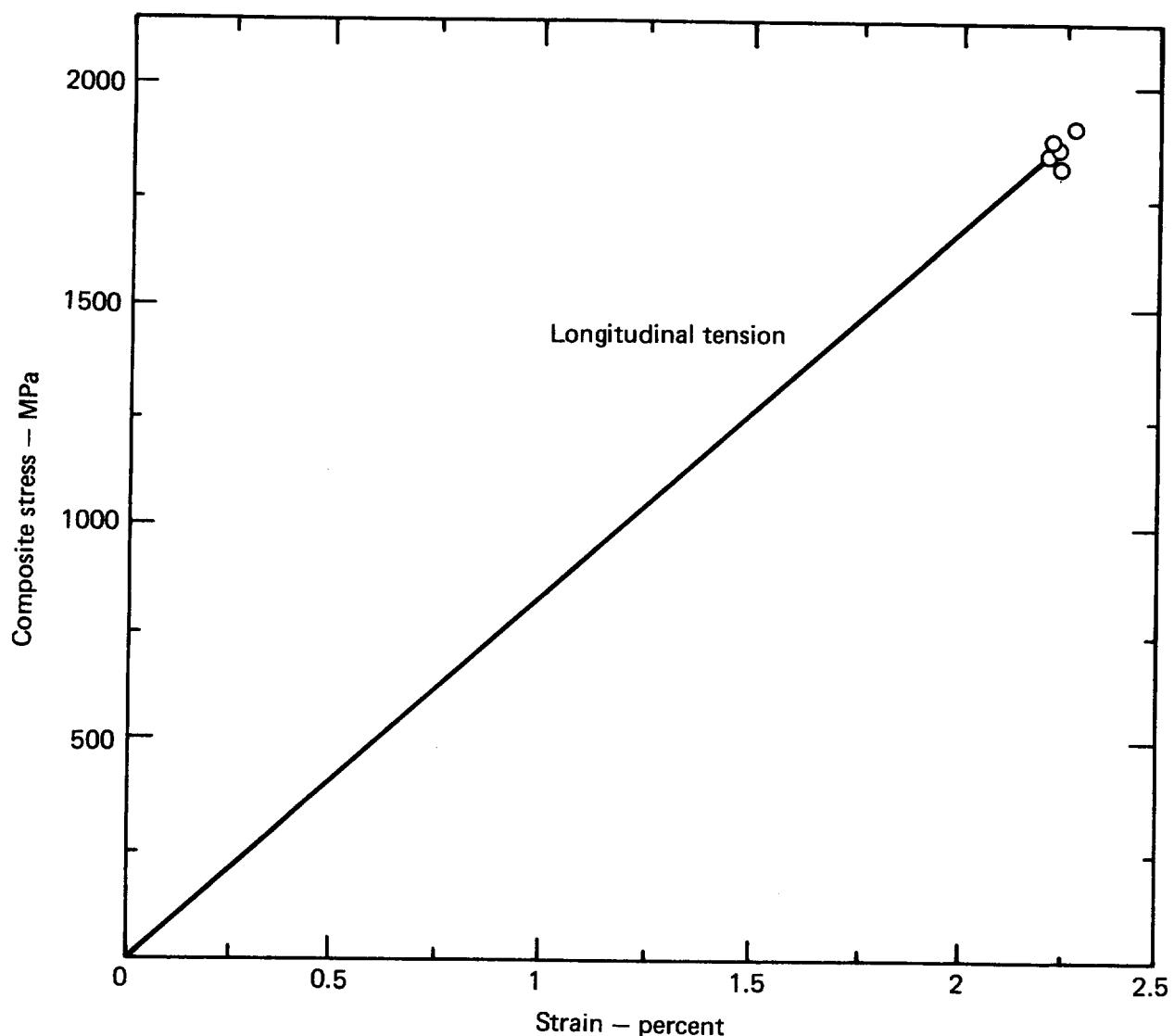


Fig. 4. Average longitudinal tensile stress-strain, with individual failure points, for Kevlar 49 in DER 332-T403 epoxy matrix. ASTM standard 2290-76 was used for all tests. Stress values are normalized to 60 vol% fiber. Actual vol% fiber: 62-64; No. of specimens: 5.

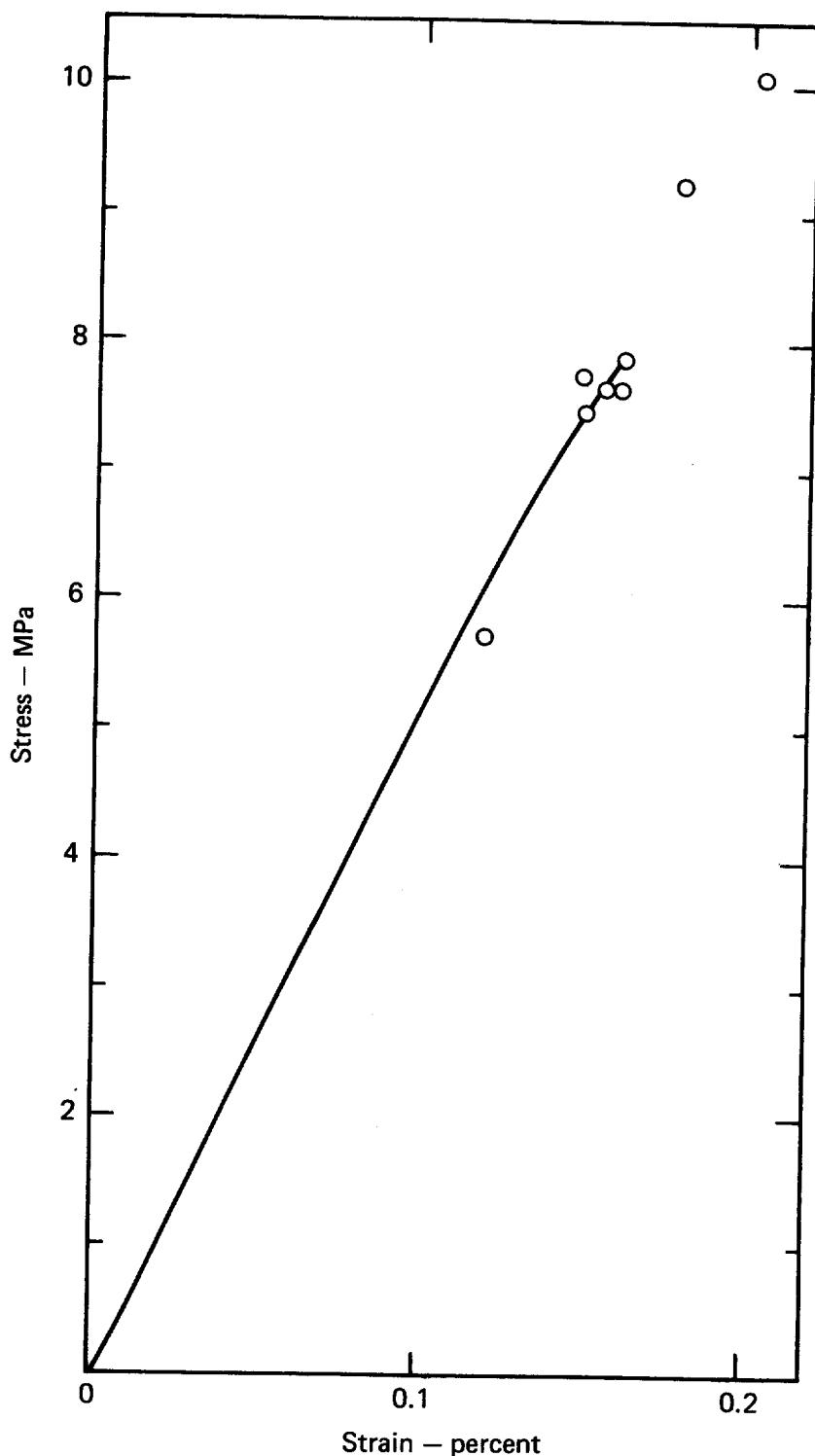


Fig. 5. Average transverse tensile stress-strain, with individual failure points, for Kevlar 49 (nominally 60 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber: 59-65; No. of specimens: 8.

Filament-Wound Composite Data Sheet 3. 60 volt E glass/DER 332-T403 epoxy⁵

Fiber: E glass: Owens-Corning Fiberglas Type 30, grade 410AA-450.

Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A epoxy resin), 45 parts Jefferson Chemical Jeffamine T-403 (polyether triamine)

Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^a

Longitudinal Young's modulus (E_{11}), GPa	48.14 ± 0.82
Transverse Young's modulus (E_{22}), GPa	12.2 ± 0.7
Shear modulus (G_{12}), GPa	5.8 ± 0.3
Major Poisson's ratio (ν_{12})	0.191 ± 0.015
Minor Poisson's ratio (ν_{21})	0.0482 ± 0.0059

Ultimates

	Tension	Compression	Shear
Longitudinal strength, MPa	1022 ± 23	490 ± 100	—
Longitudinal ultimate strain, %	2.16 ± 0.11^b	1.11 ± 0.27^b	—
Transverse strength, MPa	7.7 ± 0.5	$(78 \pm 4)^b$	—
Transverse ultimate strain, %	0.064 ± 0.010	$(0.68 \pm 0.10)^b$	—
Shear stress at 0.2% offset, MPa	—	—	22.8 ± 1.1
Shear strain at 0.2% offset, %	—	—	0.600 ± 0.040

Thermal Properties^c

Temperature, °C

-60	-20	20	50	80
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Linear coefficient of thermal

expansion, ($10^{-6}/^{\circ}\text{C}$)

Longitudinal	6.57 ± 0.53				
Transverse	23.4	25.9	30.0	35.3	104

Thermal conductivity, (W/m·°C)

Longitudinal ^d	—	1.06	1.17	1.36	1.46
Transverse ^d	—	~0.5	~0.55	~0.6	~0.65

Heat capacity, (J/kg·°C)^b

640	750	850	900	950
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a. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.02077 ± 0.00035
S_{12} , GPa ⁻¹	-0.00397 ± 0.00024
S_{22} , GPa ⁻¹	0.0824 ± 0.0050
S_{66} , GPa ⁻¹	0.174 ± 0.009

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No. of specimens</u>
I_1 , GPa ⁻¹	0.0952 ± 0.0055
I_2 , GPa ⁻¹	0.190 ± 0.010
II_1 , GPa ⁻¹	0.0308 ± 0.0026
II_2 , GPa ⁻¹	0.0078 ± 0.0014

- b. Estimated from results for 70 vol% composite.
c. Data without confidence limits are taken from tests of only one specimen.
d. Approximations: valid within about ± 20 percent.

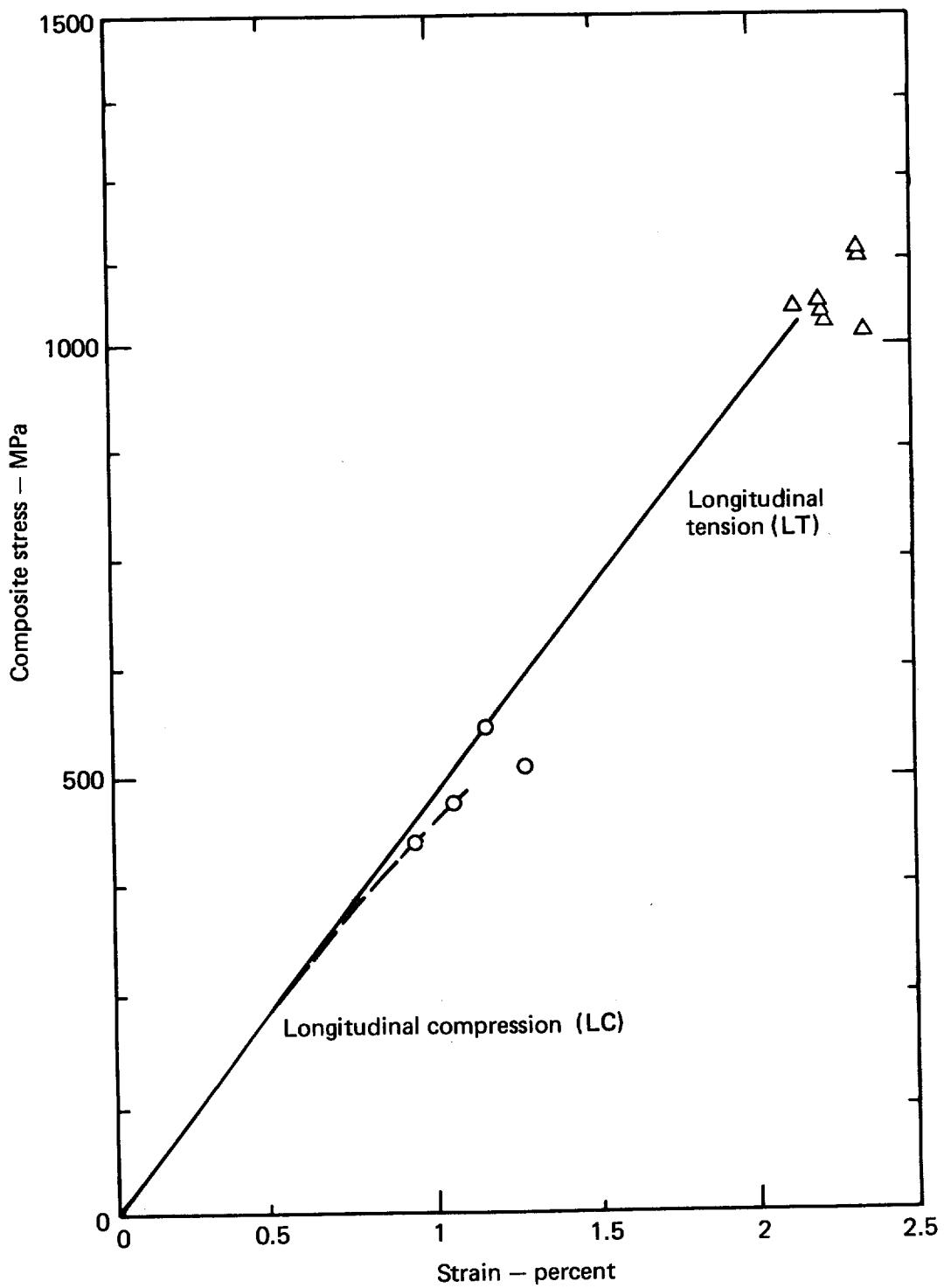


Fig. 7. Average longitudinal stress-strain, with individual failure points, for E glass in DER 332-T403 epoxy matrix. Stress values are normalized to 60 vol% fiber. Actual vol% fiber: 55-70(LT), 67.6(LC); No. of specimens: elastic constants, 24; stress, 22(LT), 4(LC); strain, 7(LT), 4(LC).

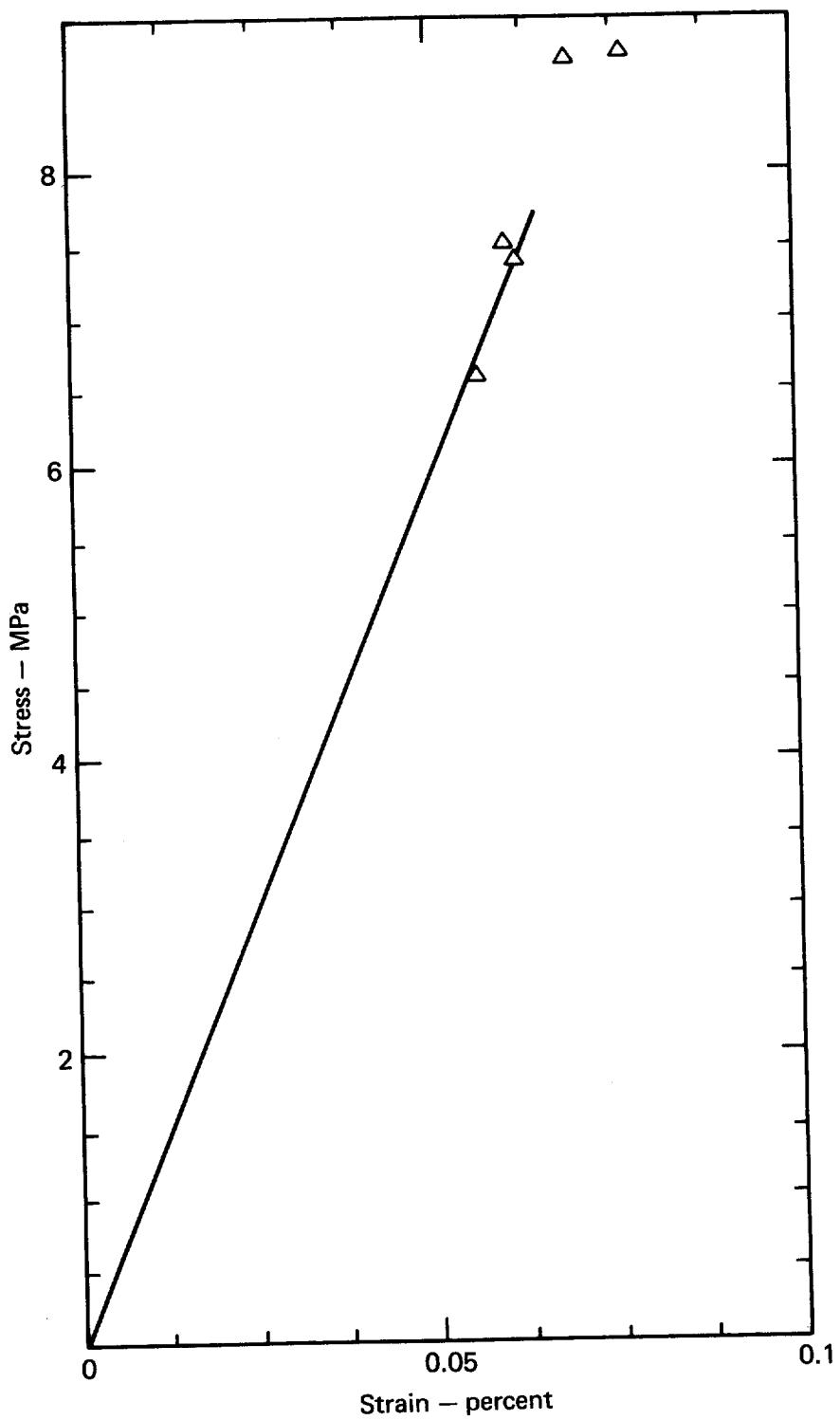


Fig. 8. Average transverse tensile stress-strain, with individual failure points, for E glass (nominally 60 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber: 62-63; No. of specimens: elastic constants, 5; stress, 7; strain, 5. Compressive behavior may be approximated by 70 vol% results.

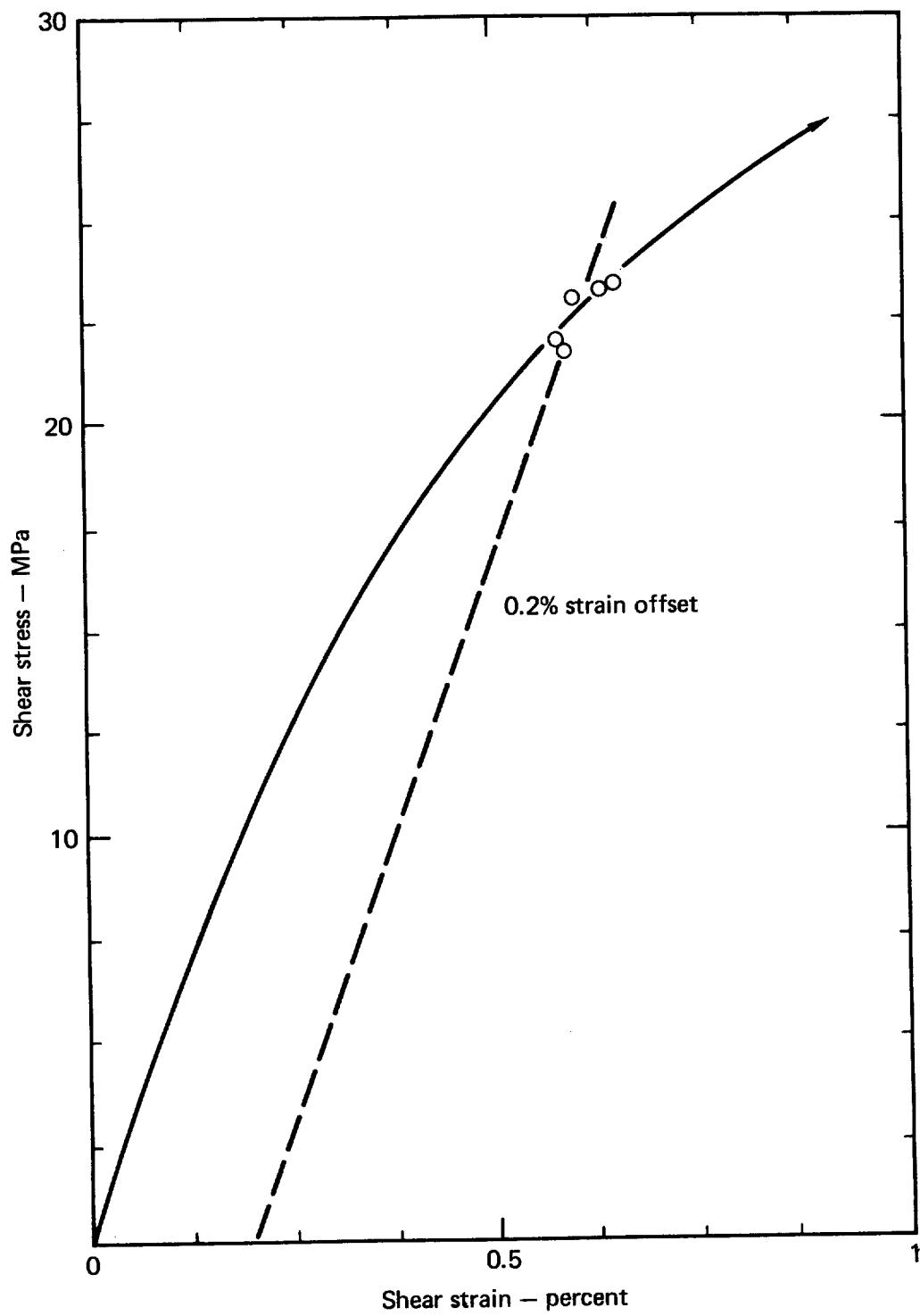


Fig. 9. Average shear stress-strain, with individual values at 0.2 percent strain offset, for E glass (nominally 60 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber, 59; No. of specimens: 5.

Filament-Wound Composite Data Sheet 4. 60 vol% E glass/DER 332-T403 epoxy⁵

Fiber: E glass: Owens-Corning Fiberglas Type 30, grade 410AA-450.

Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A epoxy resin), 45 parts Jefferson Chemical Jeffamine T-403 (polyether triamine)

Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^a

Longitudinal Young's modulus (E_{11}), GPa	52.15 ± 0.89
Transverse Young's modulus (E_{22}), GPa	14.03 ± 0.61
Shear modulus (G_{12}), GPa	6.3 ± 0.5
Major Poisson's ratio, (ν_{12})	0.207 ± 0.016
Minor Poisson's ratio, (ν_{21})	0.056 ± 0.011

Ultimates:

	Tension	Compression	Shear
Longitudinal strength, MPa	1108 ± 25	530 ± 110	-
Longitudinal ultimate strain, %	2.16 ± 0.11^b	1.11 ± 0.27^b	-
Transverse strength, MPa	7.5 ± 1.1	$(78 \pm 4)^b$	-
Transverse ultimate strain, %	0.054 ± 0.009	$(0.68 \pm 0.10)^b$	-
Shear stress at 0.2% offset, MPa	-	-	22.4 ± 1.7
Shear strain at 0.2% offset, %	-	-	0.546 ± 0.045

Thermal Properties^c

	Temperature °C				
	-60	-20	20	50	80
Linear coefficient of thermal expansion, ($10^{-6}/^\circ\text{C}$)					
Longitudinal	6.31 ± 0.51				
Transverse	20.2	22.4	25.6	30.5	90
Thermal conductivity, (W/m· °C)					
Longitudinal ^d	-	1.14	1.26	1.35	1.44
Transverse ^d	-	0.53	0.59	0.63	0.68
Heat capacity, (J/kg· °C) ^b	640	750	850	900	950

a. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01918 \pm 0.00033
S_{12} , GPa ⁻¹	-0.00397 \pm 0.00024
S_{22} , GPa ⁻¹	0.0713 \pm 0.0031
S_{66} , GPa ⁻¹	0.161 \pm 0.013

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No. of specimens</u>
I_1 , GPa ⁻¹	0.0825 \pm 0.0036
I_2 , GPa ⁻¹	0.1769 \pm 0.0023
II_1 , GPa ⁻¹	0.0261 \pm 0.0016
II_2 , GPa ⁻¹	0.00782 \pm 0.00053

- b. Estimated from results for 70 vol% composite.
- c. Data without confidence limits are taken from tests of only one specimen.
- d. Approximations: valid within about \pm 20 percent.

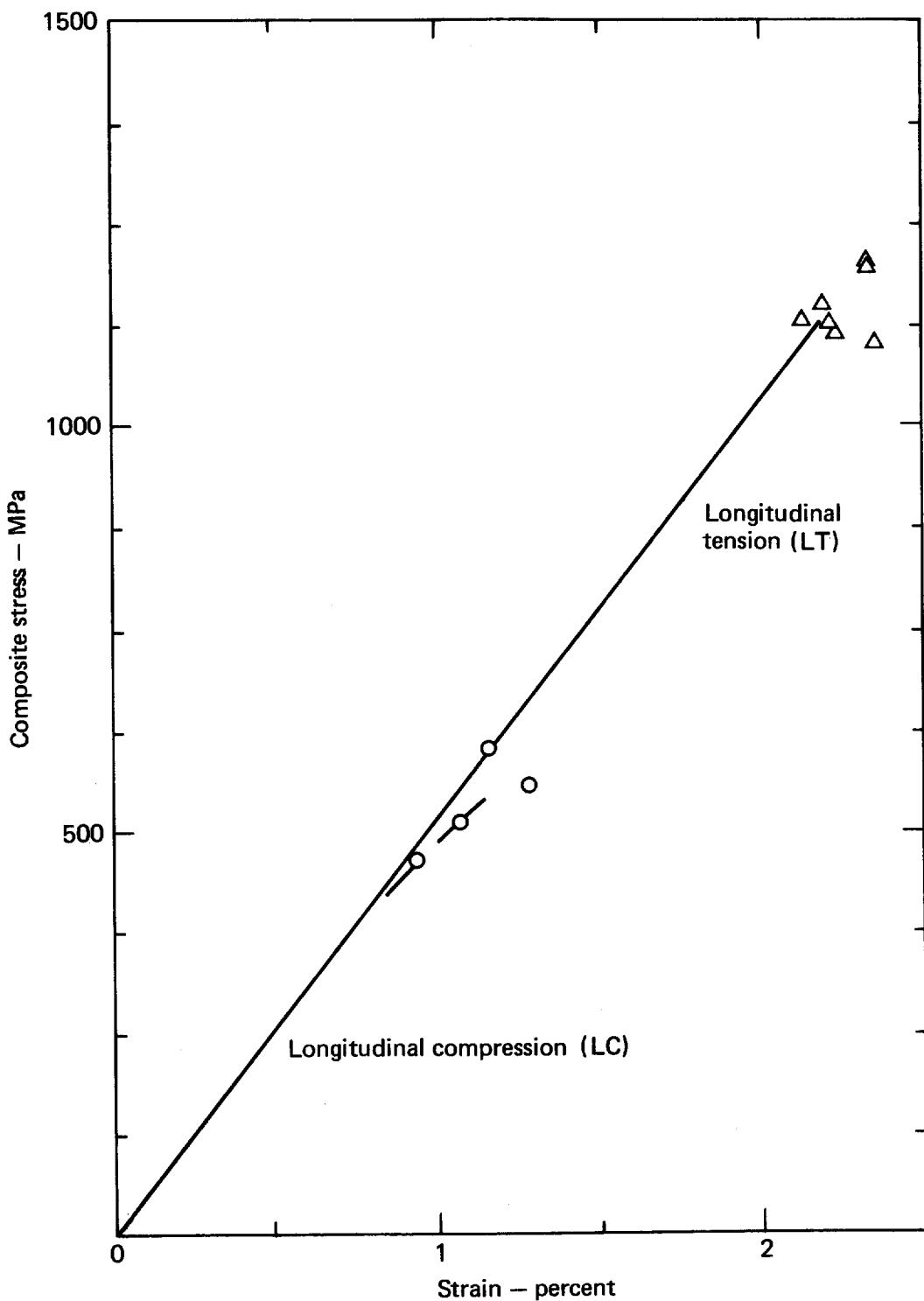


Fig. 10. Average longitudinal stress-strain, with individual failure points, for E glass in DER 332-T403 epoxy matrix. Stress values are normalized to 65 vol% fiber. Actual vol% fiber: 55-70(LT), 67.6(LC); No. of specimens: elastic constants, 24, stress, 22(LT), 4(LC), strain, 7(LT), 4(LC).

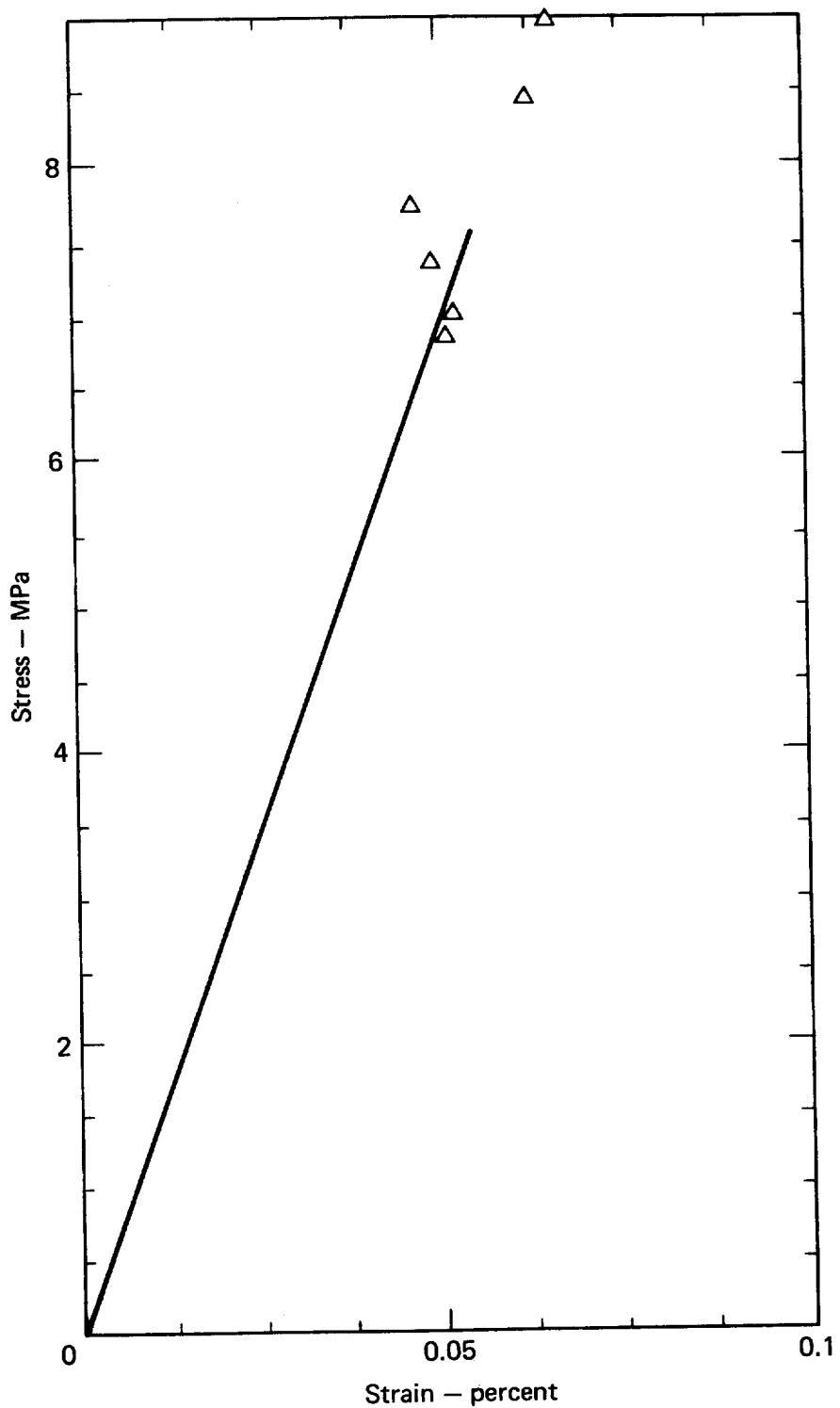


Fig. 11. Average transverse tensile stress-strain, with individual failure points, for E glass (nominally 65 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber: 66-67; No. of specimens: 6. Compressive behavior may be approximated by 70 vol% results.

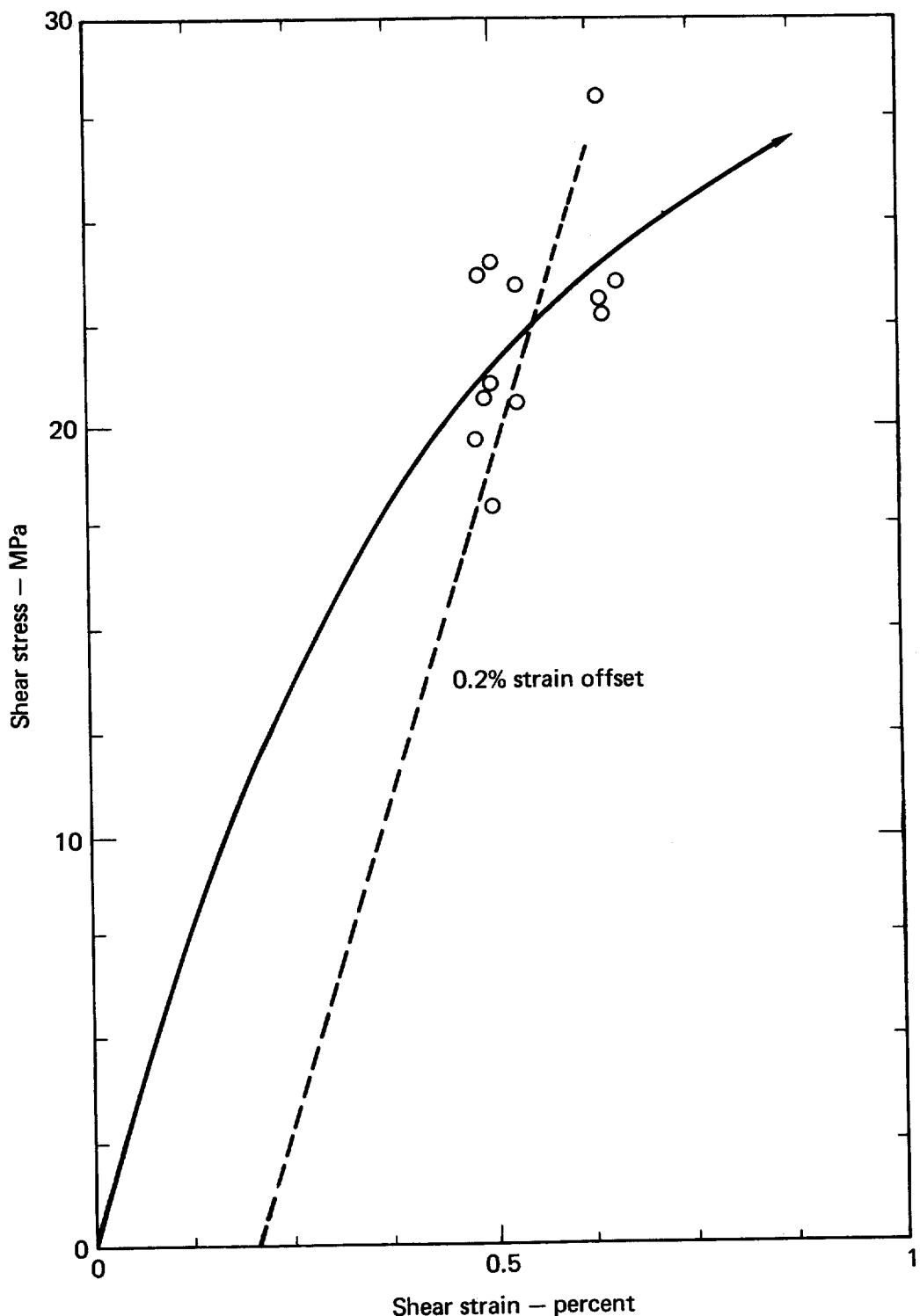


Fig. 12. Average shear stress-strain, with individual values at 0.2 percent strain offset, for E glass (nominally 65 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber, 63-65; No. of specimens: 12.

Filament-Wound Composite Data Sheet 5. 70 vol% E glass/DER 332-T403 epoxy⁵

Fiber: E glass: Owens-Corning Fiberglas Type 30, grade
410AA-450

Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A
epoxy resin), 45 parts Jefferson Chemical
Jeffamine T-403 (polyether triamine)

Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^a

Longitudinal Young's modulus (E_{11}), GPa	56.16 ± 0.96
Transverse Young's modulus (E_{22}), GPa	17.30 ± 1.04
Shear modulus (G_{12}), GPa	7.4 ± 0.5
Major Poisson's ratio (ν_{12})	0.233 ± 0.017
Minor Poisson's ratio (ν_{21})	0.0681 ± 0.0091

Ultimates	Tension	Compression	Shear	
Longitudinal strength, MPa	1183 ± 29	570 ± 120	—	
Longitudinal ultimate strain, %	2.16 ± 0.11	1.11 ± 0.27	—	
Transverse strength, MPa	6.20 ± 0.5	78 ± 4	—	
Transverse ultimate strain, %	0.042 ± 0.030	0.68 ± 0.10	—	
Shear stress at 0.2% offset, MPa	—	—	26.8 ± 1.5	
Shear strain at 0.2% offset, %	—	—	0.568 ± 0.023	

Thermal Properties^b

	Temperature, °C				
	-60	-20	20	50	80
Linear coefficient of thermal expansion, ($10^{-6}/°C$)					
Longitudinal	6.07 ± 0.49	6.07 ± 0.49	6.07 ± 0.49	6.07 ± 0.49	6.07 ± 0.49
Transverse	17.1	18.9	21.6	25.8	76
Thermal conductivity, (W/m·°C)					
Longitudinal ^c	—	1.23	1.35	1.44	1.53
Transverse ^c	—	0.50	0.56	0.58	0.61
Heat capacity, (J/kg·°C)	640	750	850	900	950

a. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01781 \pm 0.00030
S_{12} , GPa ⁻¹	-0.00397 \pm 0.00024
S_{22} , GPa ⁻¹	0.0583 \pm 0.0039
S_{66} , GPa ⁻¹	0.136 \pm 0.009

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No. of specimens</u>
I_1 , GPa ⁻¹	0.0682 \pm 0.0040
I_2 , GPa ⁻¹	0.152 \pm 0.010
II_1 , GPa ⁻¹	0.0202 \pm 0.0020
II_2 , GPa ⁻¹	0.0165 \pm 0.0018

- b. Data without confidence limits are taken from tests of only one specimen.
c. Approximations: valid within about \pm 20 percent.

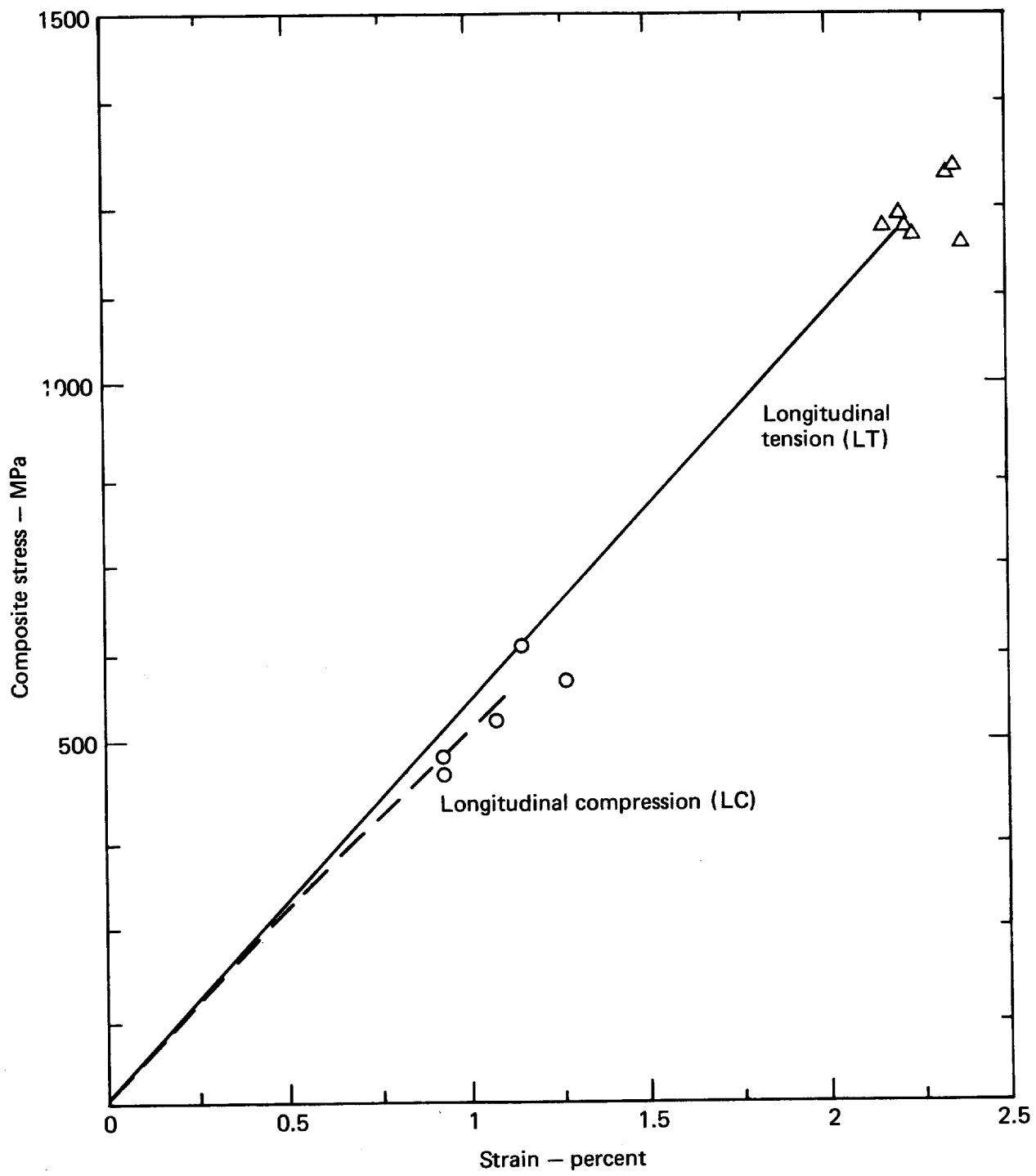


Fig. 13. Average longitudinal stress-strain, with individual failure points, for E glass in DER 332-T403 epoxy matrix. Stress values are normalized to 70 vol% fiber. Actual vol% fiber: 55-70(LT), 67.6(LC); No. of specimens: elastic constants, 24; stress, 22(LT), 4(LC); strain, 7(LT), 4(LC).

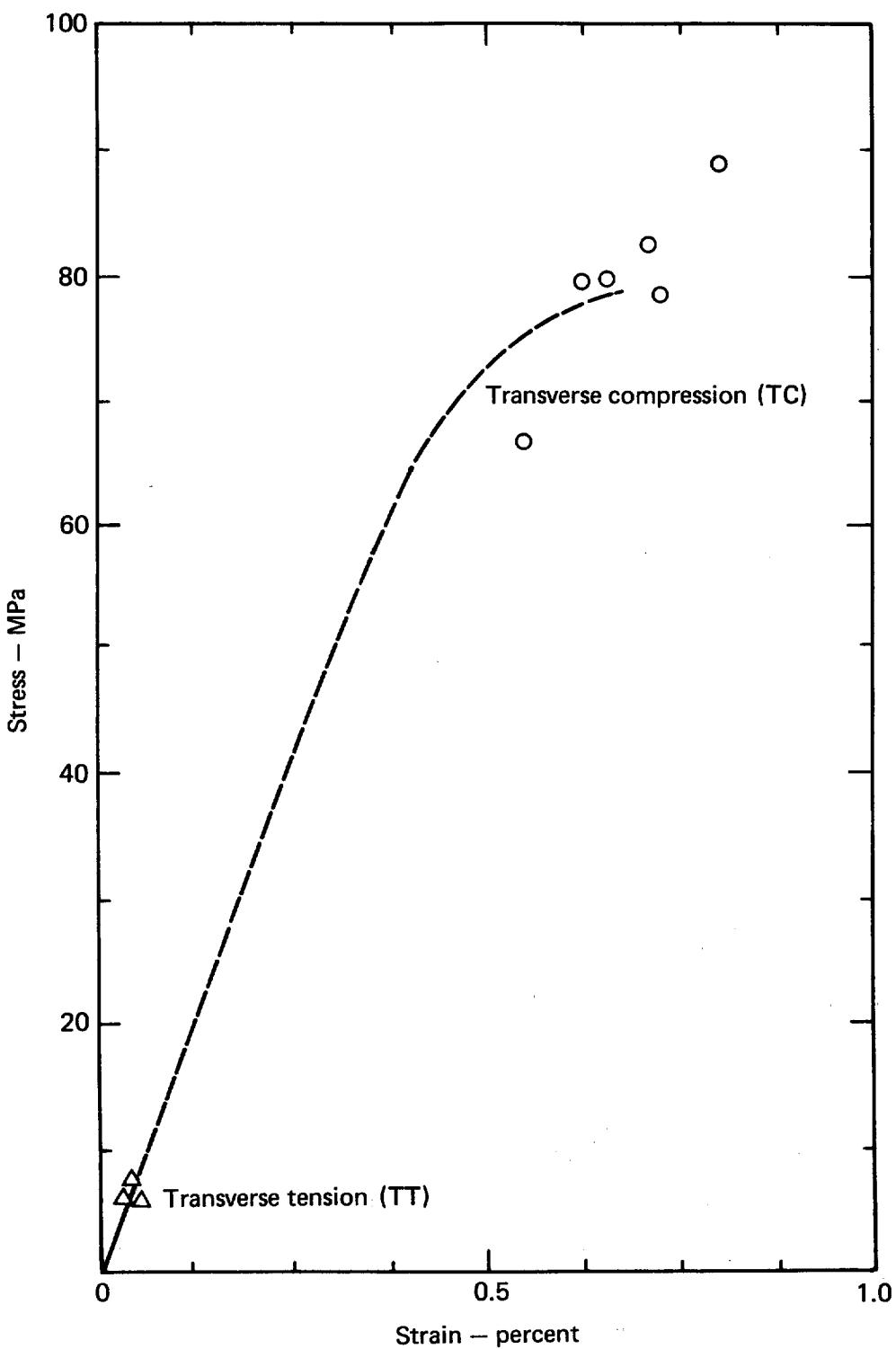


Fig. 14. Average transverse stress-strain, with individual failure points, for E glass (nominally 65 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber, 67-69(TT), 67.6(TC); No. of specimens: elastic constants, 12; stress, 3(TT), 11(TC); strain, 3(TT), 6(TC).

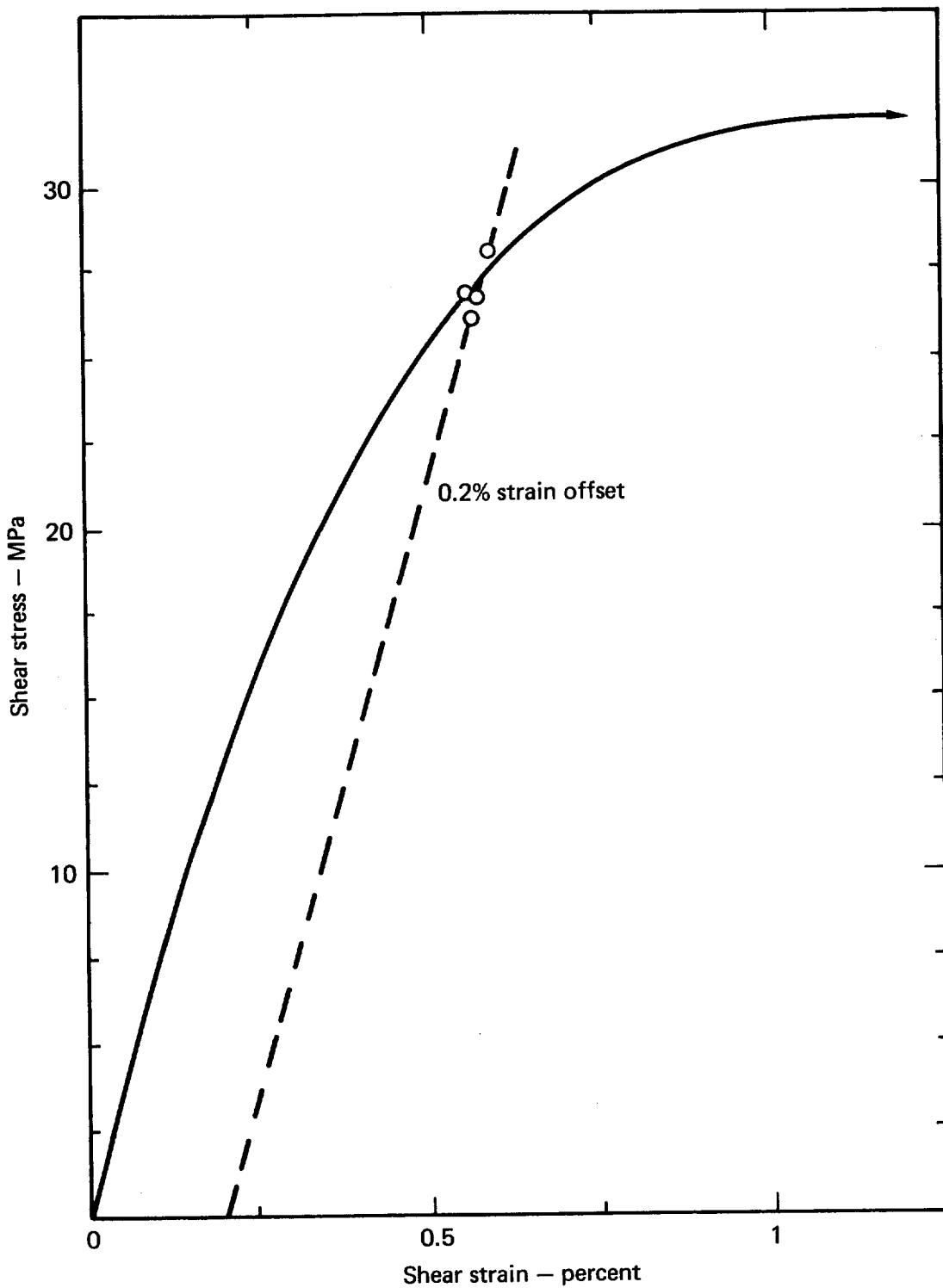


Fig. 15. Average shear stress-strain, with individual values at 0.2 percent strain offset, for E glass (nominally 70 vol%) in DER 332-T403 epoxy matrix. Actual vol% fiber, 67.9; No. of specimens: 4.

Filament-Wound Composite Data Sheet 6. 50 vol% S-2 glass/DER 332-T403 epoxy⁶

Fiber: S-2 glass: Owens-Corning Fiberglas grade P263A-750^a
 Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A
 epoxy resin), 45 parts Jefferson Chemical
 Jeffamine 7403 (polyether triamine)
 Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^b

Longitudinal Young's modulus (E_{11}), GPa	45.23 ± 0.89
Transverse Young's modulus (E_{22}), GPa	12.73 ± 0.24
Shear modulus (G_{12}), GPa	$(4.18 \pm 0.19)^c$
Major Poisson's ratio (ν_{12})	0.2653 ± 0.0057
Minor Poisson's ratio (ν_{21})	0.0749 ± 0.0020

Ultimates

	Tension	Compression	Shear
Longitudinal strength, MPa	1346 ± 52	380 ± 50	—
Longitudinal ultimate strain, %	2.93 ± 0.14	0.93 ± 0.07^d	—
Transverse strength, MPa	35.62 ± 0.95	$(111.6 \pm 2.3)^d$	—
Transverse ultimate strain, %	0.314 ± 0.010	$(3.89 \pm 0.47)^d$	—
Shear stress at 0.2% offset, MPa	—	—	$(26.71 \pm 0.39)^c$
Shear Strain at 0.2% offset, %	—	—	$(0.823 \pm 0.014)^c$

Thermal Properties^b

	Temperature °C					
	-50	-25	0	25	50	75
Linear coefficient of thermal expansion, ($10^{-6}/^\circ\text{C}$)						
Longitudinal ^e	(4.083 ± 0.038)					
Transverse ^f	(23.5 ± 0.8)	(24.3 ± 0.8)	(26.3 ± 0.8)	(28.9 ± 0.8)	(32.7 ± 3.4)	(98 ± 21)
Thermal conductivity, (W/m·°C)						
Longitudinal ^e	—	—	1.26 ± 0.26	1.34 ± 0.26	1.42 ± 0.26	1.50 ± 0.26
Transverse	—	—	—	—	—	—
Heat capacity, (J/kg·°C)	—	—	—	—	—	—

- a. Now replaced by commercial grade 463AA-750.
- b. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.02216 \pm 0.00044
S_{12} , GPa ⁻¹	-0.00588 \pm 0.00011
S_{22} , GPa ⁻¹	0.07855 \pm 0.00081
S_{66} , GPa ⁻¹	(0.2395 \pm 0.0033)

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No.</u>
	<u>of specimens</u>
I_1 , GPa ⁻¹	0.08895 \pm 0.00098
I_2 , GPa ⁻¹	(0.2630 \pm 0.0034)
II_1 , GPa ⁻¹	0.02820 \pm 0.00048
II_2 , GPa ⁻¹	(0.01588 \pm 0.00044)

- c. Extrapolated from tests of specimens ranging from 62 to 69 vol% fiber.
- d. Taken from results of 65 vol% fiber.
- e. Extrapolated from tests of specimens ranging from 60 to 70 vol% fiber.
- f. Results at 60 vol% fiber.

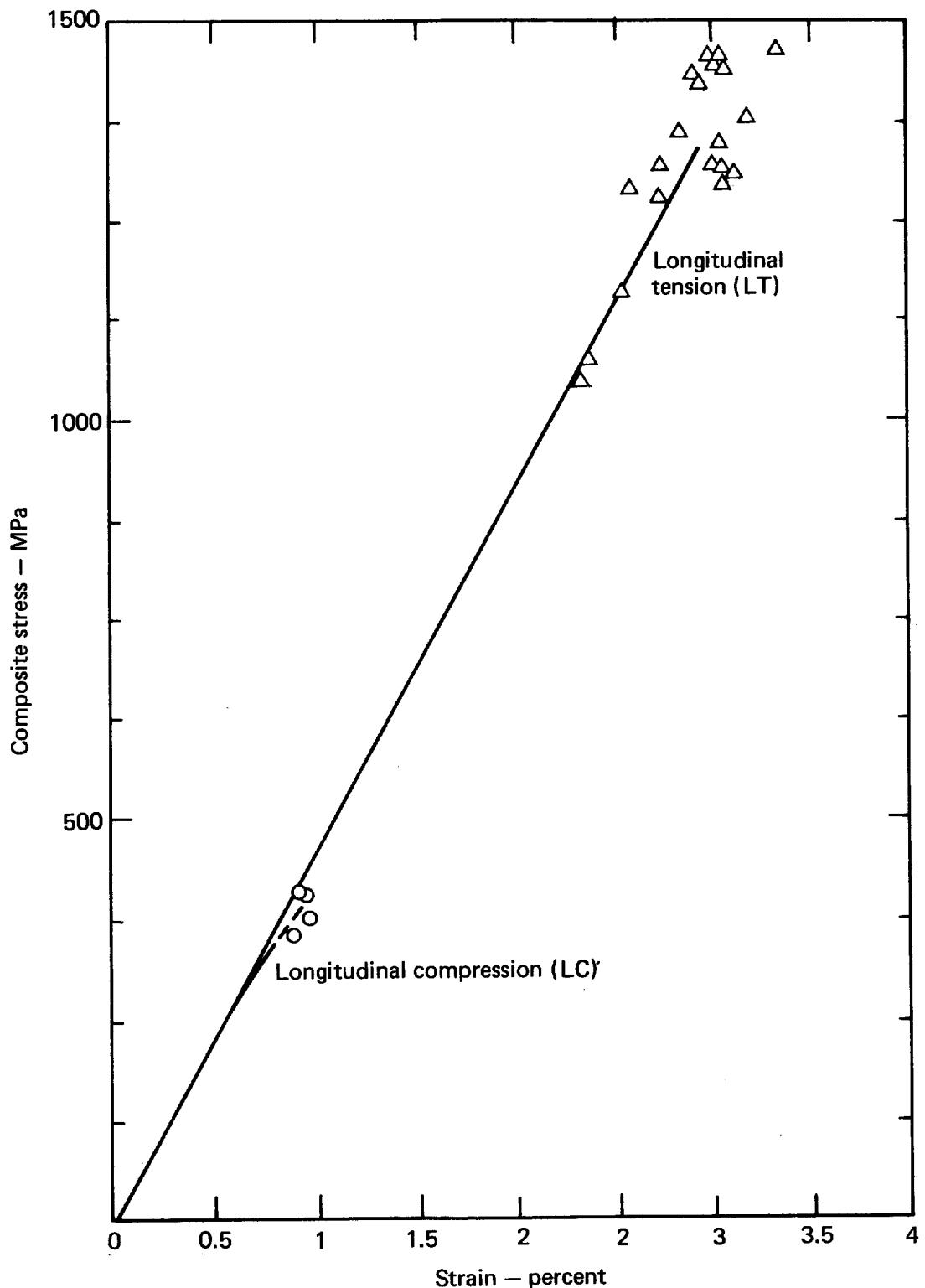


Fig. 16. Average longitudinal stress-strain, with individual failure points, for S-2 glass in DER 332-T403 epoxy matrix. Stress values are normalized to 50 vol% fiber. Actual vol% fiber: 41-64(LT), 63.4(LC); No. of specimens: elastic constants, 31; stress, 29(LT), 4(LC); strain, 6(LT), 4(LC).

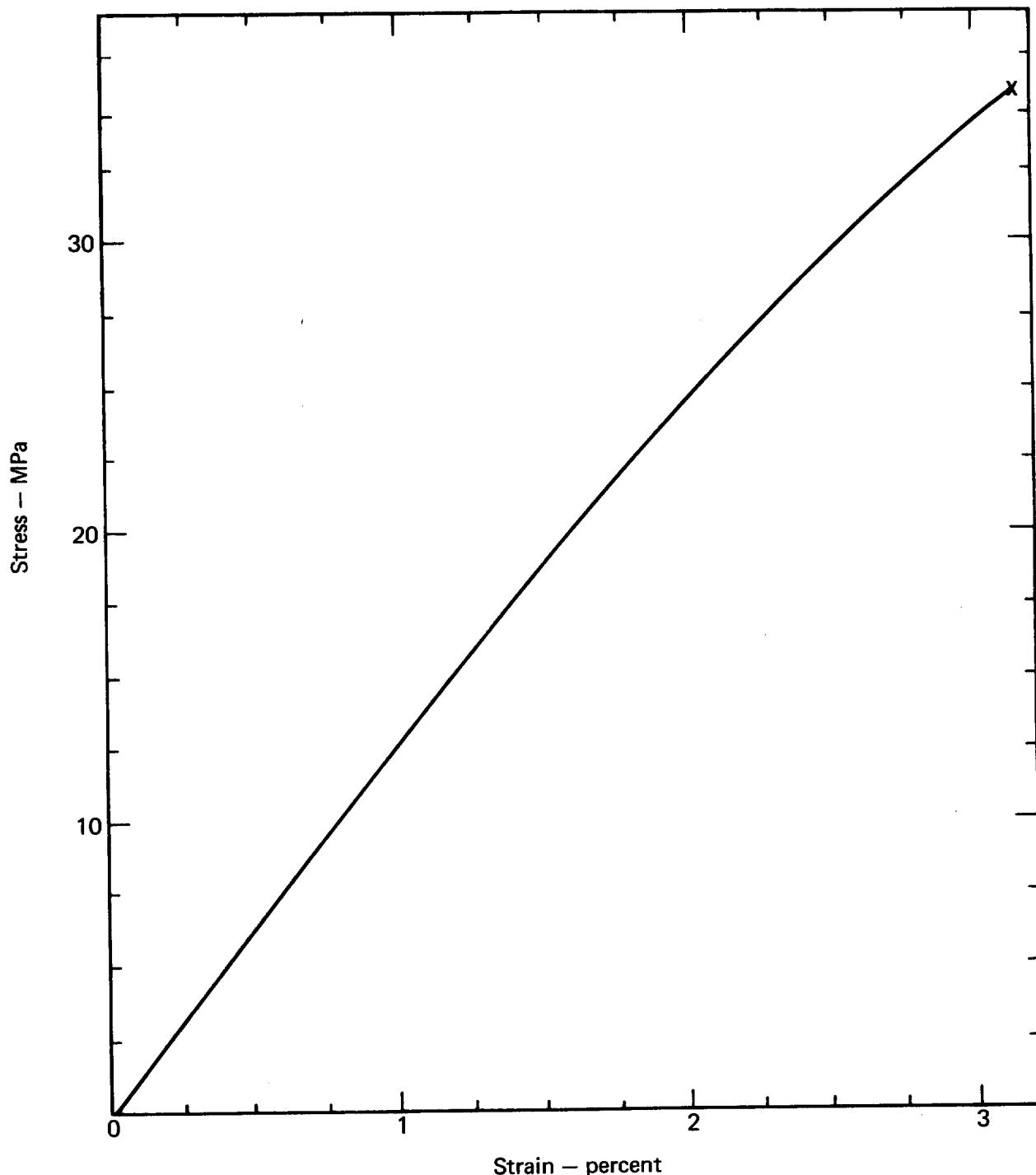


Fig. 17. Average transverse tensile stress-strain for S-2 glass (50 vol%) in DER 332-T403 epoxy matrix. Curve data are interpolated from tests of 29 specimens, 44-68 vol% fiber. Compressive behavior may be approximated by 65 vol% results.

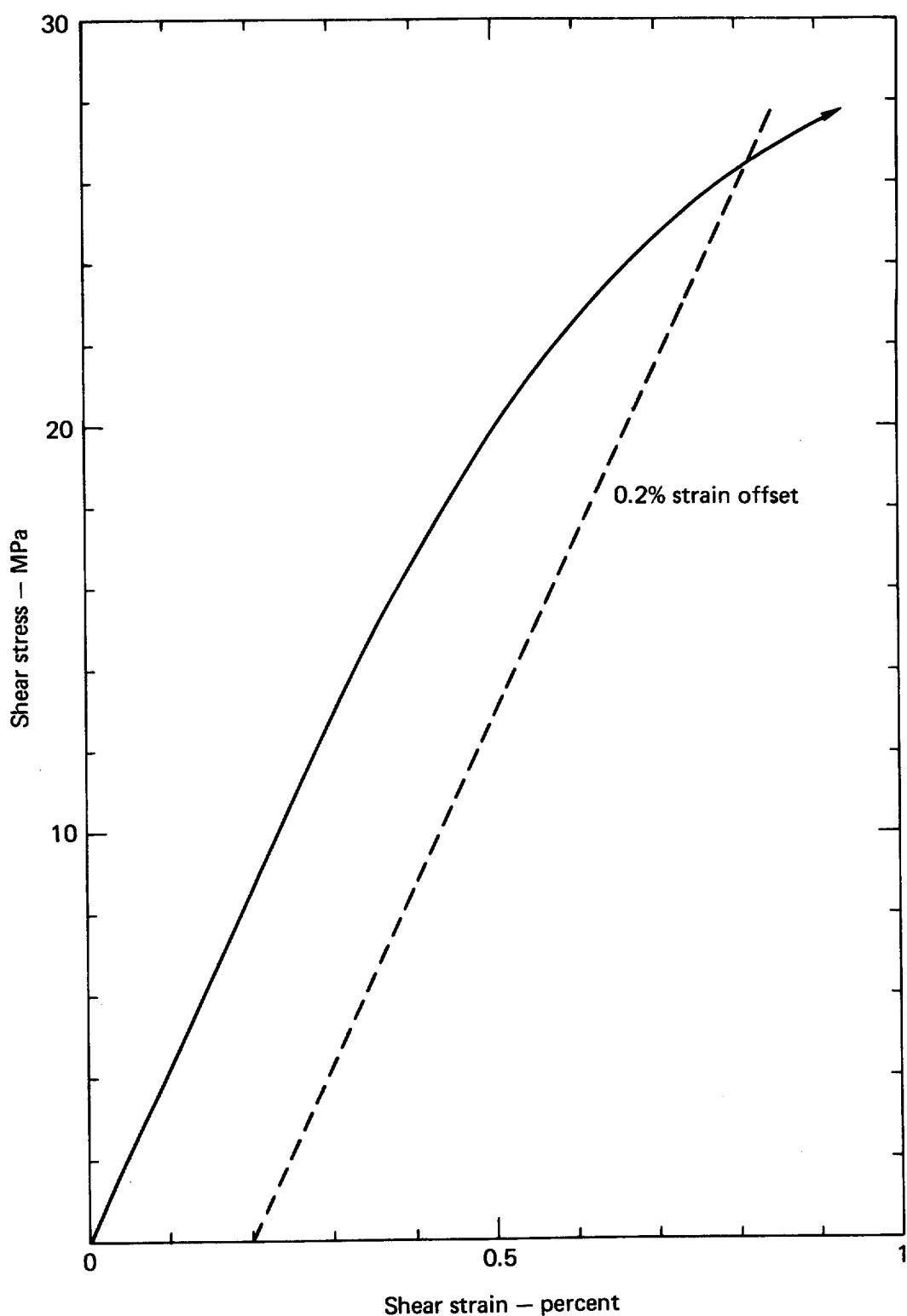


Fig. 18. Average shear stress-strain for S-2 glass (50 vol%) in DER 332-T403 epoxy matrix. Curve data are extrapolated from tests of 20 specimens, 62-69 vol% fiber.

Filament-Wound Composite Data Sheet 7. 55 vol% S-2 glass/DER 332-T403 epoxy⁶

Fiber: S-2 glass: Owens-Corning Fiberglas grade P263A-750^a
 Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A
 epoxy resin), 45 parts Jefferson Chemical
 Jeffamine T-403 (polyether triamine)
 Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^b

Longitudinal Young's modulus (E_{11}), GPa	49.75 ± 0.98
Transverse Young's modulus (E_{22}), GPa	14.28 ± 0.24
Shear modulus (G_{12}), GPa	$(5.11 \pm 0.19)^c$
Major Poisson's ratio (ν_{12})	0.2651 ± 0.0057
Minor Poisson's ratio (ν_{21})	0.0763 ± 0.0021

Ultimates

	Tension	Compression	Shear
Longitudinal strength, MPa	1480 ± 57	420 ± 50	—
Longitudinal ultimate strain, %	3.07 ± 0.02	0.93 ± 0.07^d	—
Transverse strength, MPa	37.76 ± 0.95	$(111.6 \pm 2.3)^d$	—
Transverse ultimate strain, %	0.294 ± 0.010	$(3.89 \pm 0.47)^d$	—
Shear stress at 0.2% offset, MPa	—	—	$(27.90 \pm 0.39)^c$
Shear strain at 0.2% offset, %	—	—	$(0.743 \pm 0.014)^c$

Thermal Properties

	Temperature, °C					
	-50	-25	0	25	50	75
Linear coefficient of thermal expansion, ($10^{-6}/°C$)						
Longitudinal ^e	(3.870 ± 0.038)					
Transverse ^f	(23.5 ± 0.8)	(24.3 ± 0.8)	(26.3 ± 0.8)	(28.9 ± 0.8)	(32.7 ± 3.4)	(98 ± 21)
Thermal conductivity, (W/m.°C)						
Longitudinal ^e	—	—	1.38 ± 0.26	1.46 ± 0.26	1.55 ± 0.26	1.63 ± 0.26
Transverse	—	—	—	—	—	—
Heat capacity, (J/kg.°C)	—	—	—	—	—	—

-
- a. Now replaced by commercial grade 463AA-750.
- b. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.02014 \pm 0.00040
S_{12} , GPa ⁻¹	-0.00534 \pm 0.00010
S_{22} , GPa ⁻¹	0.07003 \pm 0.00081
S_{66} , GPa ⁻¹	0.1957 \pm 0.0033

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No.</u> <u>of specimens</u>
I_1 , GPa ⁻¹	0.07949 \pm 0.00098
I_2 , GPa ⁻¹	(0.2171 \pm 0.0033)
II_1 , GPa ⁻¹	0.02494 \pm 0.00047
II_2 , GPa ⁻¹	(0.01186 \pm 0.00044)

- c. Extrapolated from tests of specimens ranging from 62 to 60 vol% fiber.
- d. Taken from results at 65 vol% fiber.
- e. Extrapolated from tests of specimens ranging from 60 to 70 vol% fiber.
- f. Results at 60 vol% fiber.

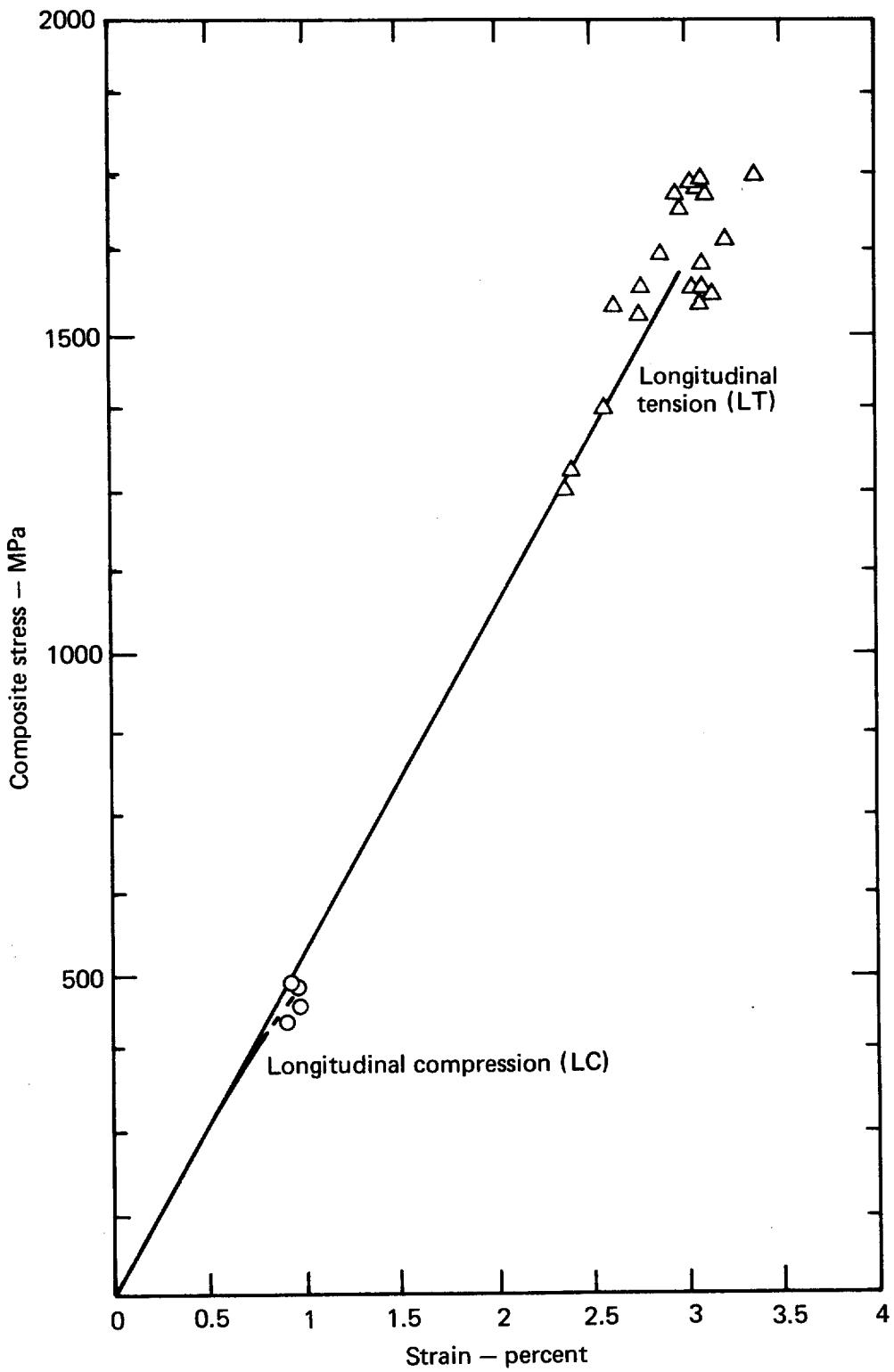


Fig. 19. Average longitudinal stress-strain, with individual failure points, for S-2 glass in DER 332-T403 epoxy matrix. Stress values are normalized to 55 vol% fiber. Actual vol% fiber: 41-64(LT), 63.4(LC); No. of specimens: elastic constants, 31, stress, 29(LT), 4(LC), strain, 6(LT), 4(LC).

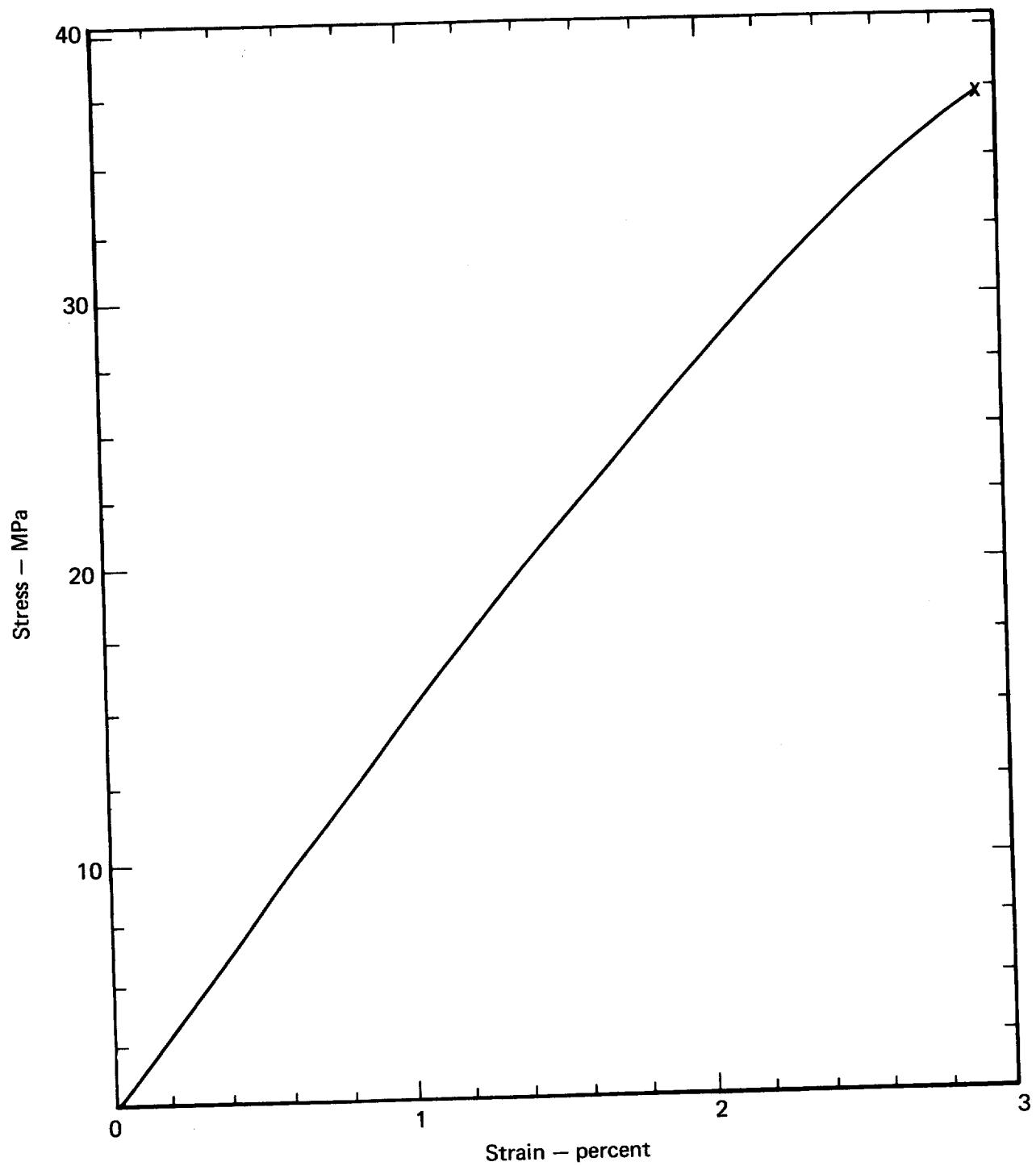


Fig. 20. Average transverse tensile stress-strain for S-2 glass (55 vol%) in DER 332-T403 epoxy matrix. Curve data are interpolated from tests of 29 specimens, 44-68 vol% fiber. Compressive behavior may be approximated by 65 vol% fiber results.

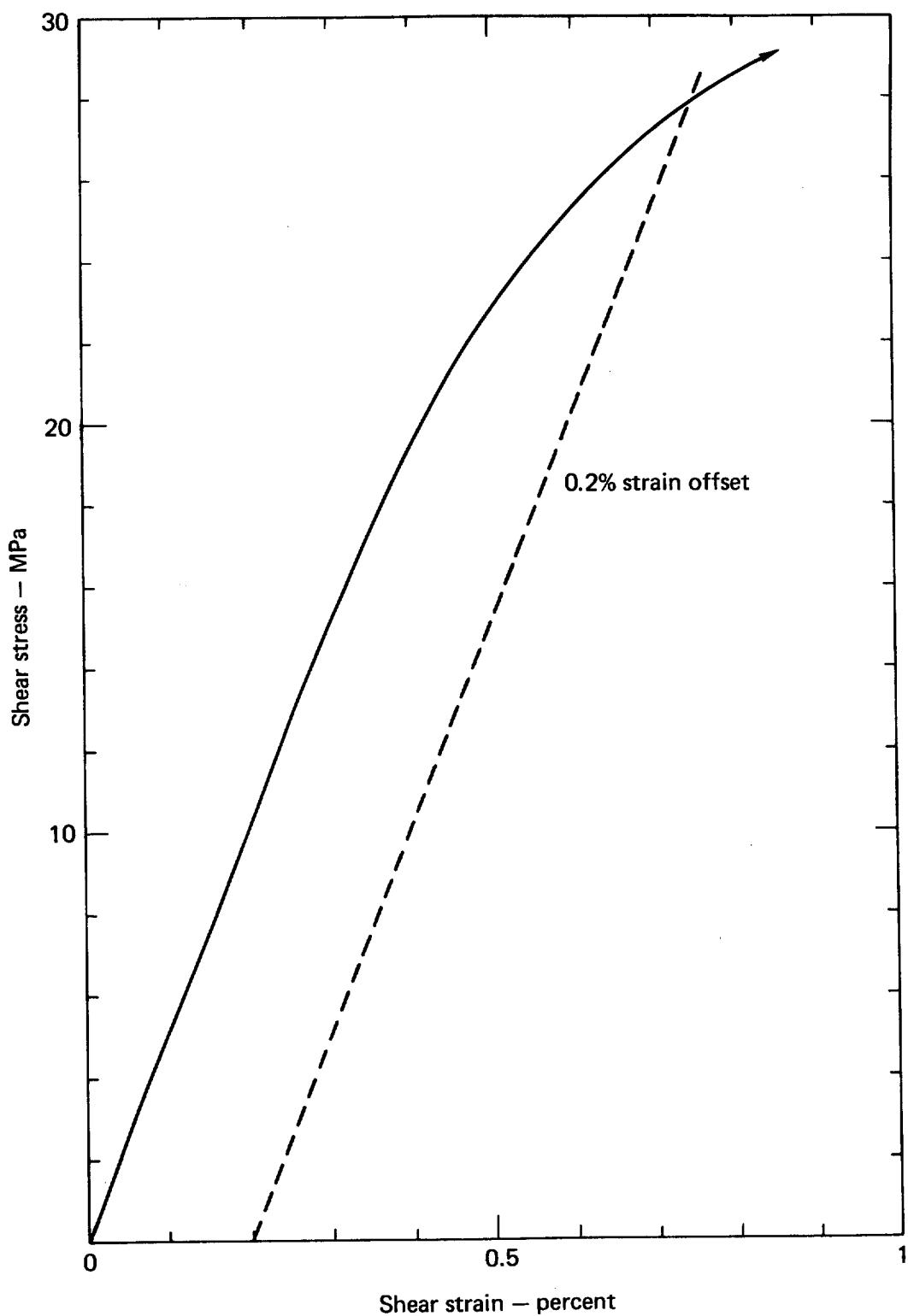


Fig. 21. Average shear stress-strain for S-2 glass (55 vol%) in DER 332-T403 epoxy matrix. The curve data are extrapolated from tests of 20 specimens, 62-69 vol% fiber.

Filament-Wound Composite Data Sheet 8. 60 vol% S-2 glass/DER 332-T403 epoxy⁶

Fiber: S-2 glass: Owens Corning Fiberglas grade P263A-750^a
 Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A
 epoxy resin), 45 parts Jefferson Chemical
 Jeffamine T-403 (polyether triamine)
 Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^b

Longitudinal Young's modulus (E_{11}), GPa	54.28 \pm 1.07
Transverse Young's modulus (E_{22}), GPa	15.85 \pm 0.24
Shear modulus (G_{12}), GPa	6.14 \pm 0.19
Major Poisson's ratio (ν_{12})	0.2653 \pm 0.0057
Minor Poisson's ratio (ν_{21})	0.0777 \pm 0.0022

Ultimates

	Tension	Compression	Shear
Longitudinal strength, MPa	1615 \pm 62	460 \pm 60	—
Longitudinal ultimate strain, %	3.12 \pm 0.09	0.93 \pm 0.07 ^c	—
Transverse strength, MPa	39.82 \pm 0.95	(111.6 \pm 2.3) ^c	—
Transverse ultimate strain, %	0.277 \pm 0.010	(3.89 \pm 0.47) ^c	—
Shear stress at 0.2% offset, MPa	—	—	29.04 \pm 0.39
Shear strain at 0.2% offset, %	—	—	0.676 \pm 0.014

Thermal Properties

	Temperature, °C					
	-50	-25	0	25	50	75
Linear coefficient of thermal expansion, ($10^{-6}/^{\circ}\text{C}$)						
Longitudinal	3.523 \pm 0.038					
Transverse	23.5 \pm 0.8	24.3 \pm 0.8	26.3 \pm 0.8	28.9 \pm 0.8	32.7 \pm 3.4	98 \pm 21
Thermal conductivity, (W/m·°C)						
Longitudinal	—	—	1.50 \pm 0.26	1.58 \pm 0.26	1.67 \pm 0.26	1.75 \pm 0.26
Transverse ^d	0.477	0.509	0.540	0.571	0.603	0.634
Heat capacity, (J/kg·°C)	—	—	—	—	—	—

-
- a. Now replaced by commercial grade 463AA-750.
- b. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01847 \pm 0.00037
S_{12} , GPa ⁻¹	-0.00490 \pm 0.00010
S_{22} , GPa ⁻¹	0.06309 \pm 0.00081
S_{66} , GPa ⁻¹	0.1628 \pm 0.0033

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum number of specimens</u>
I_1 , GPa ⁻¹	0.07176 \pm 0.00096
I_2 , GPa ⁻¹	0.1824 \pm 0.0033
II_1 , GPa ⁻¹	0.02231 \pm 0.00046
II_2 , GPa ⁻¹	0.00893 \pm 0.00044

- c. Taken from results at 65 vol% fiber.
- d. Data taken from a single specimen.

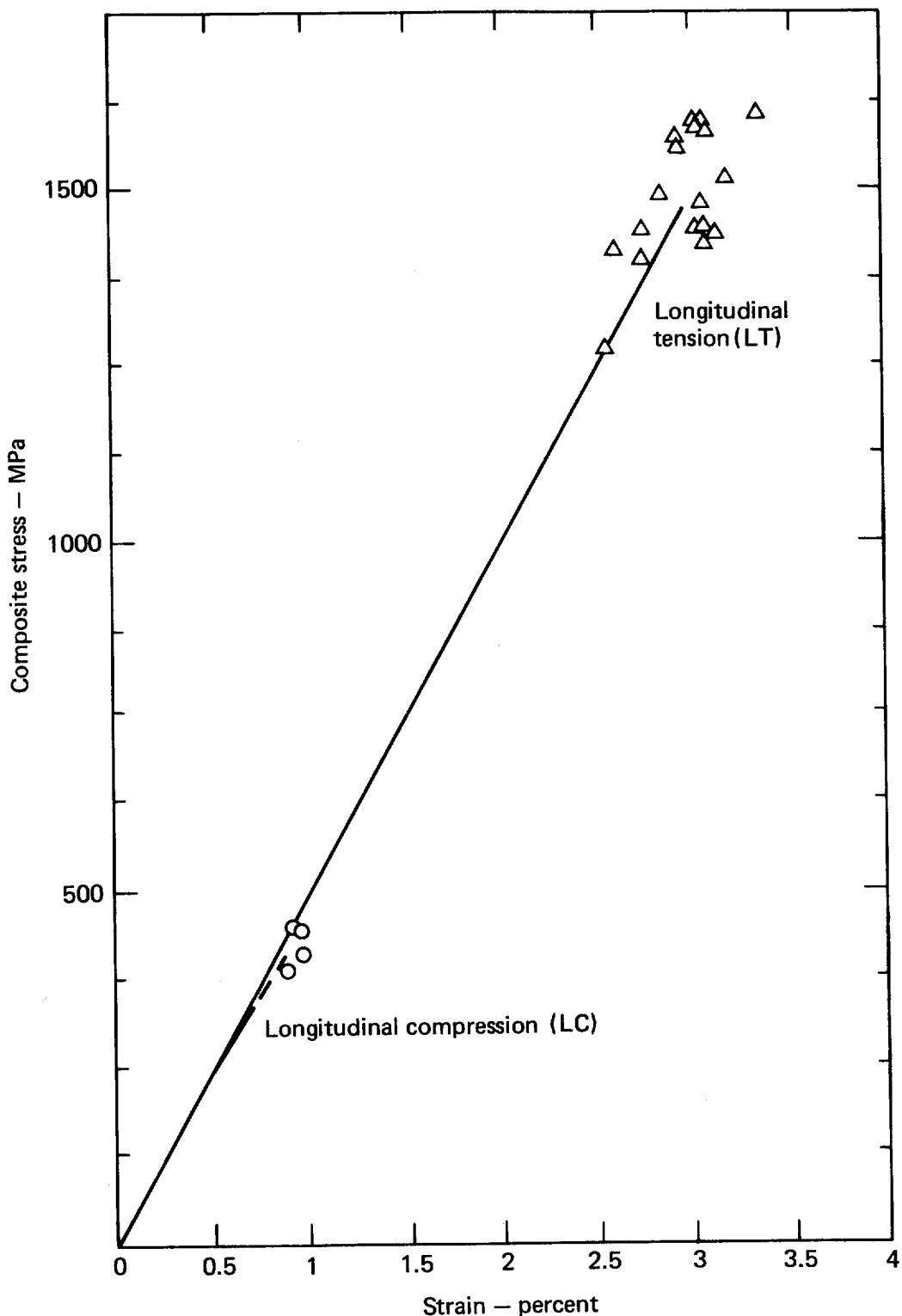


Fig. 22. Average longitudinal stress-strain, with individual failure points, for S-2 glass in DER 332-T403 epoxy matrix. Stress values are normalized to 60 vol% fiber. Actual vol% fiber: 41-64(LT), 63.4(LC); No. of specimens: elastic constants, 31, stress, 29(LT), 4(LC), strain, 9(LT), 4(LC).

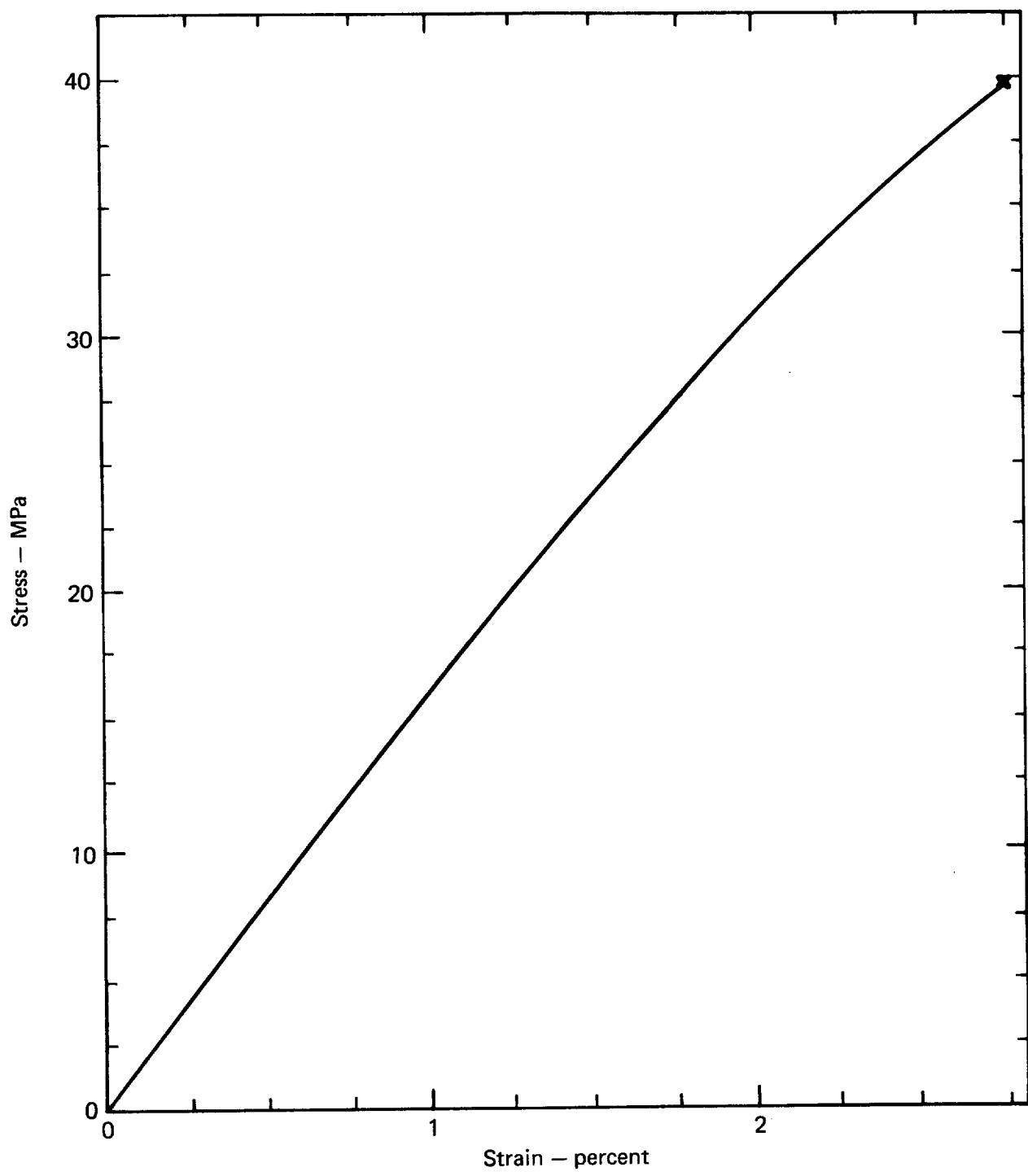


Fig. 23. Average transverse tensile stress-strain for S-2 glass (60 vol%) in DER 332-T403 epoxy matrix. The curve is interpolated from tests of 29 specimens, 44-68 vol% fiber. Compressive behavior may be approximated by 65 vol% fiber.

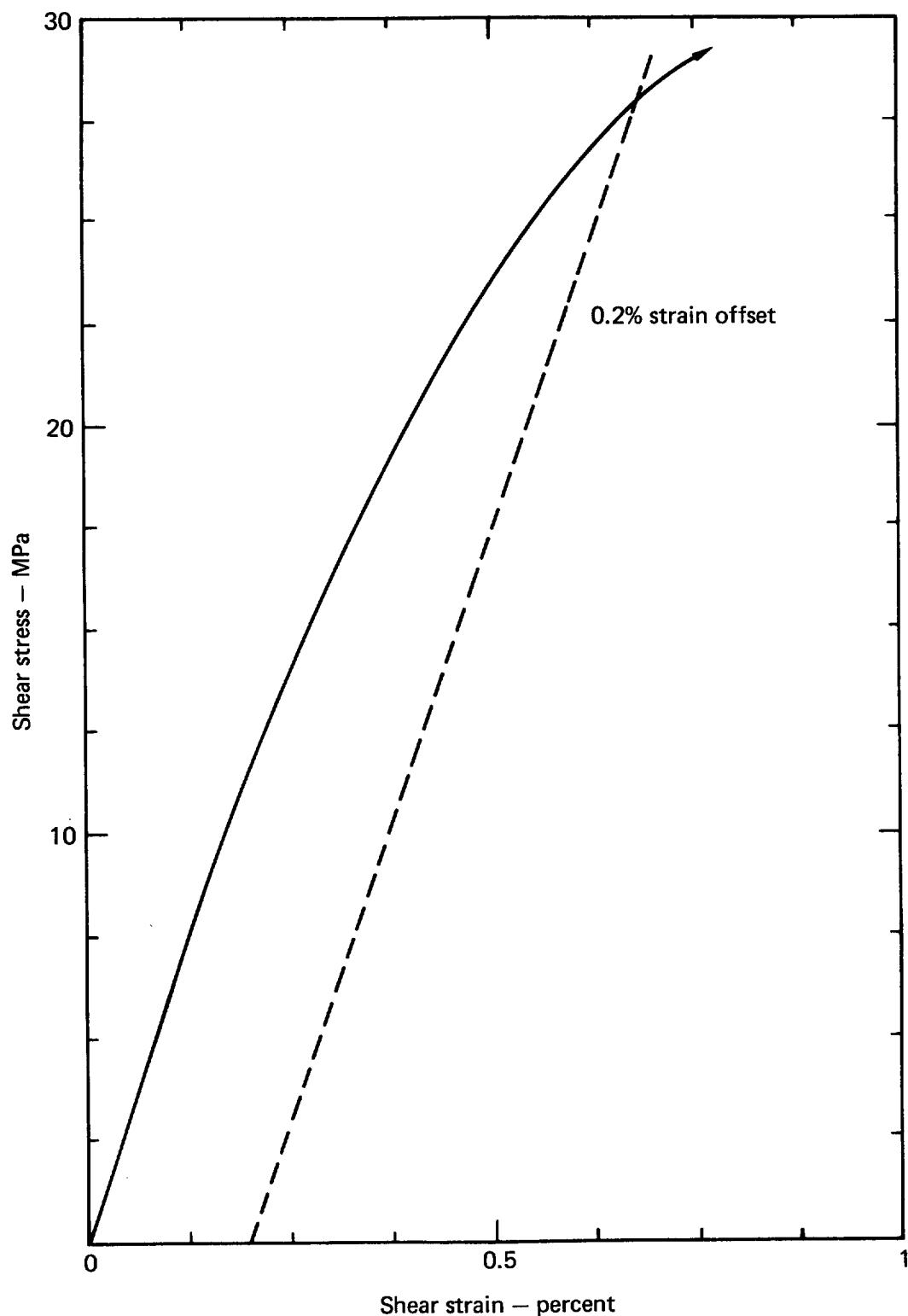


Fig. 24. Average shear stress-strain for S-2 glass (60 vol%) in DER 332-T403 epoxy matrix. Curve data are extrapolated from tests of 20 specimens, 62-69 vol% fiber.

Filament-Wound Composite Data Sheet 9. 65 vol% S-2 glass/DER 332-T403 epoxy⁶

Fiber: S-2 glass: Owens Corning Fiberglas grade P263A-750^a
 Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A
 epoxy resin), 45 parts Jefferson Chemical
 Jeffamine 7403 (polyether triamine)
 Cure: 16 h at 60°C

Mechanical Properties

Elastic constants^b

Longitudinal Young's modulus (E_{11}), GPa	58.80 ± 1.16
Transverse Young's modulus (E_{22}), GPa	17.46 ± 0.24
Shear modulus (G_{12}), GPa	7.28 ± 0.19
Major Poisson's ratio (ν_{12})	0.2651 ± 0.0057
Minor Poisson's ratio (ν_{21})	0.0789 ± 0.0023

Ultimates

	Tension	Compression	Shear
Longitudinal strength, MPa	1749 ± 67	500 ± 60	—
Longitudinal ultimate strain, %	2.87 ± 0.27	0.93 ± 0.07	—
Transverse strength, MPa	41.81 ± 0.95	111.6 ± 2.3	—
Transverse ultimate strain, %	0.263 ± 0.010	3.89 ± 0.47	—
Shear stress at 0.2% offset, MPa	—	—	30.12 ± 0.39
Shear strain at 0.2% offset, %	—	—	0.620 ± 0.014

Thermal Properties

	Temperature, °C					
	-50	-25	0	25	50	75
Linear coefficient of thermal expansion, ($10^{-6}/^{\circ}\text{C}$)						
Longitudinal	3.523 ± 0.038					
Transverse	19.9 ± 0.8	21.3 ± 0.8	23.2 ± 0.8	25.1 ± 0.8	27.6 ± 3.4	77 ± 21
Thermal conductivity, (W/m·°C)						
Longitudinal	—	—	1.62 ± 0.26	1.70 ± 0.26	1.80 ± 0.26	1.88 ± 0.26
Transverse	—	—	—	—	—	—
Heat capacity, (J/kg·°C)	—	—	—	—	—	—

-
- a. Now replaced by commercial grade 463AA-750.
- b. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01705 \pm 0.00034
S_{12} , GPa ⁻¹	-0.00452 \pm 0.00009
S_{22} , GPa ⁻¹	0.05727 \pm 0.00081
S_{66} , GPa ⁻¹	0.1374 \pm 0.0033

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No.</u>
	<u>of specimens</u>
I_1 , GPa ⁻¹	0.06528 \pm 0.00094
I_2 , GPa ⁻¹	0.1555 \pm 0.0033
II_1 , GPa ⁻¹	0.02011 \pm 0.00045
II_2 , GPa ⁻¹	0.00676 \pm 0.00044

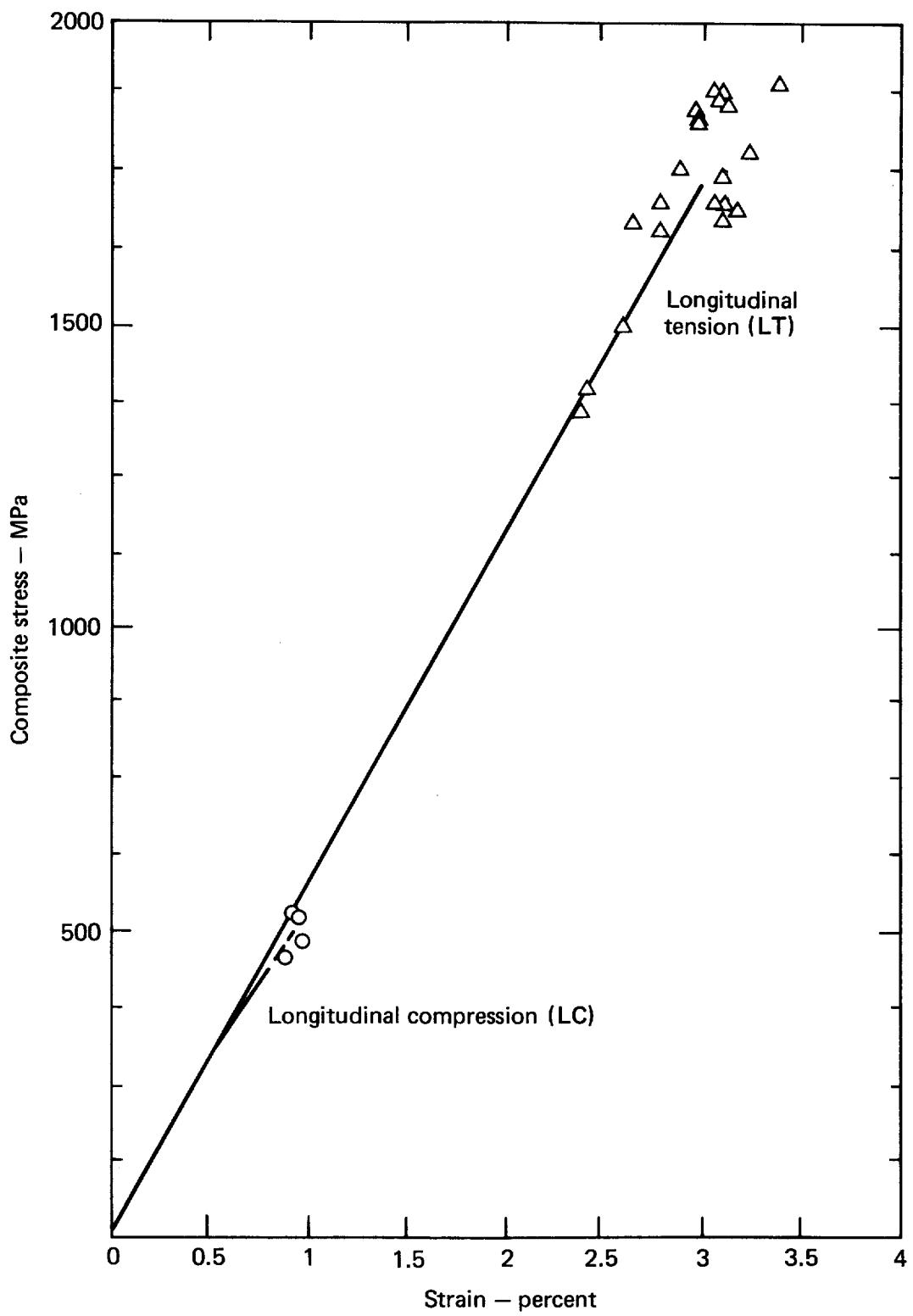


Fig. 25. Average longitudinal stress-strain, with individual failure points, for S-2 glass in DER 332-T403 epoxy matrix. Stress values are normalized to 65 vol% fiber. Actual vol% fiber: 41-64(LT), 63.4(LC); No. of specimens: elastic constants, 31, stress, 29(LT), 4(LC), strain, 10(LT), 4(LC).

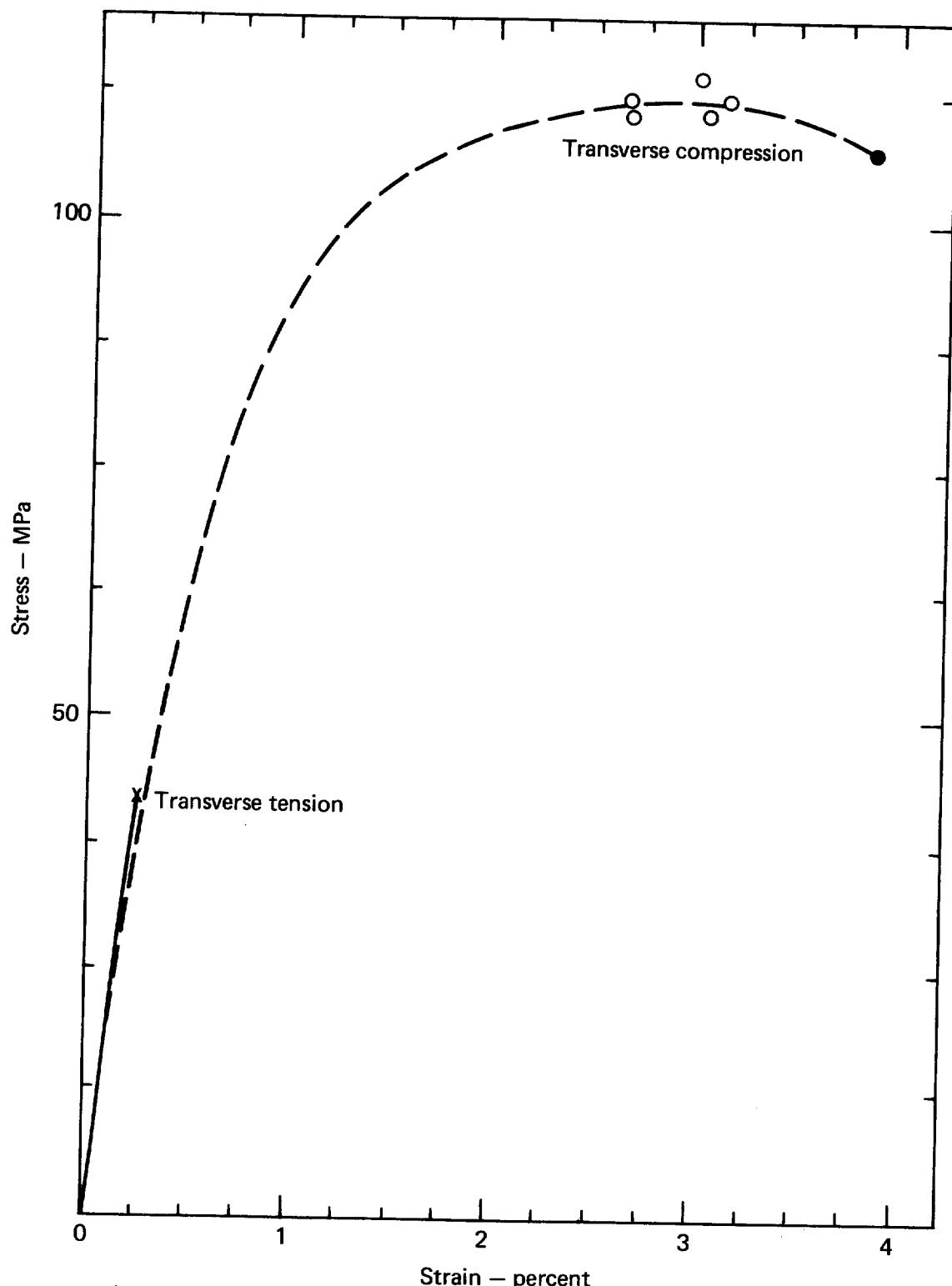


Fig. 26. Average transverse stress-strain for S-2 glass (65 vol%) in DER 332-T403 epoxy matrix. Transverse tension curve is interpolated from tests of 29 specimens, 44-68 vol% fiber. Compression curve is from tests of 5 specimens, 63.4 vol% fiber. Individual values at ultimate stress are shown for compression specimens.

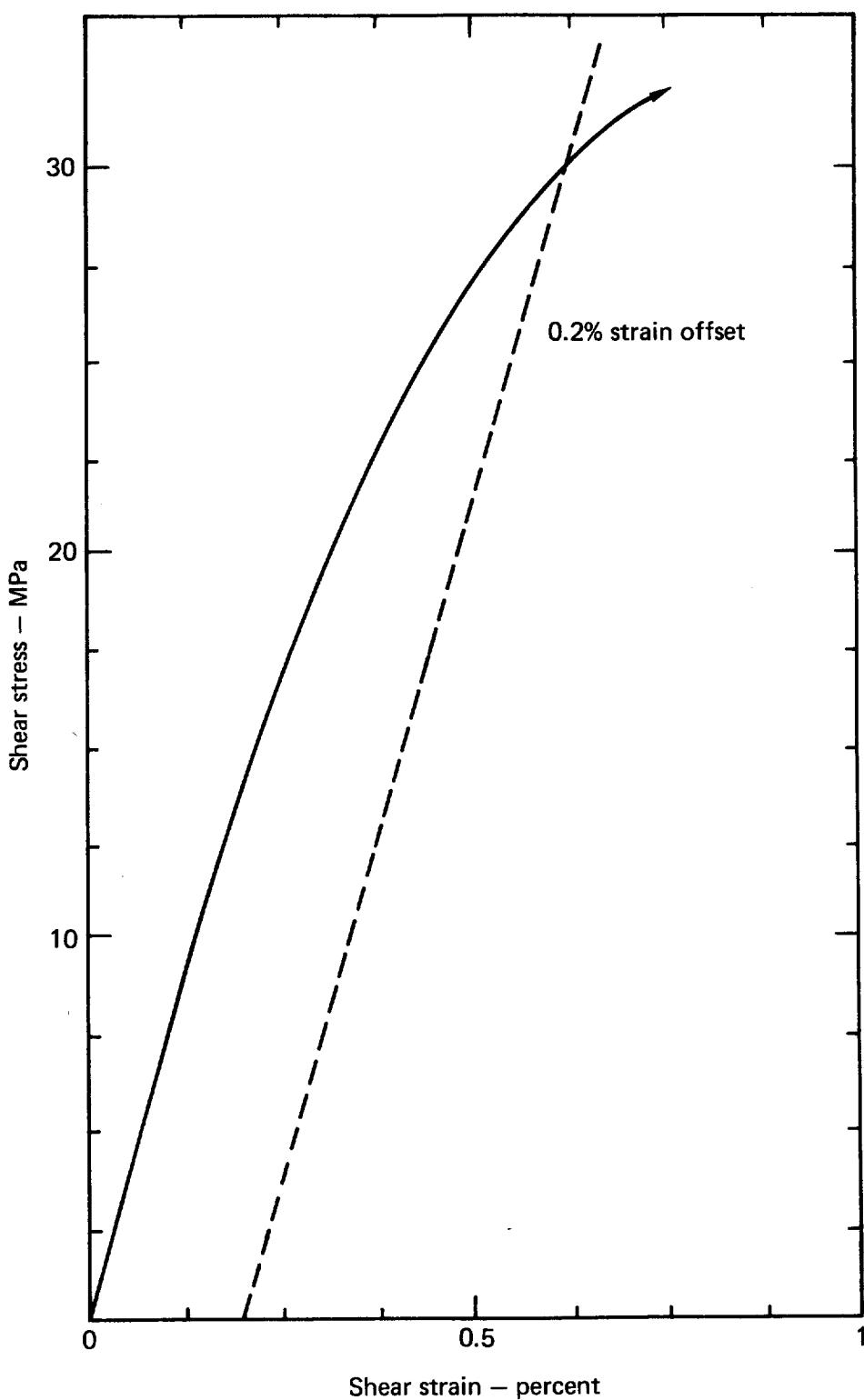


Fig. 27. Average shear stress-strain for S-2 glass (65 vol%) in DER 332-T403 epoxy matrix. Curve data are interpolated from tests of 20 specimens, 62-69 vol% fiber.

Filament-Wound Composite Data Sheet 10. 70 vol% S-2 glass/DER 332-T403 epoxy⁶

Fiber: S-2 glass: Owens Corning Fiberglas Grade P263A-750^a
Matrix: 100 parts Dow Chemical DER 332 (bisphenol-A
epoxy resin), 45 parts Jefferson Chemical
Jeffamine 7403 (polyether triamine)
Cure: 16 h at 60°C

Mechanical Properties

Elastic Constants^b

Longitudinal Young's modulus (E_{11}), GPa	63.32 ± 1.25
Transverse Young's modulus (E_{22}), GPa	19.09 ± 0.24
Shear modulus (G_{12}), GPa	8.52 ± 0.19
Major Poisson's ratio (ν_{12})	0.2655 ± 0.0057
Minor Poisson's Ratio (ν_{21})	0.0802 ± 0.0024

Ultimates

	Tension	Compression	Shear
Longitudinal strength, MPa	1884 ± 72	540 ± 70	—
Longitudinal ultimate strain, %	2.57 ± 0.32	0.93 ± 0.07^c	—
Transverse strength, MPa	43.75 ± 0.95	$(111.6 \pm 2.3)^c$	—
Transverse ultimate strain, %	0.250 ± 0.010	$(3.89 \pm 0.47)^c$	—
Shear stress at 0.2% offset, MPa	—	—	31.16 ± 0.39
Shear strain at 0.2% offset, %	—	—	0.573 ± 0.014

Thermal Properties

Temperature, °C

-50 -25 0 25 50 75

Linear coefficient of thermal
expansion, ($10^{-6}/^{\circ}\text{C}$)

Longitudinal	3.379 ± 0.038					
Transverse	21.3 ± 0.8	23.4 ± 0.8	24.9 ± 0.8	27.6 ± 0.8	29.6 ± 3.4	86 ± 21

Thermal conductivity, (W/m·°C)

Longitudinal	—	—	1.74 ± 0.26	1.82 ± 0.26	1.92 ± 0.26	2.00 ± 0.26
Transverse	—	—	—	—	—	—

Heat capacity, (J/kg·°C)

—	—	—	—	—	—	—
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-
- a. Now replaced by commercial grade 463AA-750.
- b. We obtained the following values for the non-zero compliance components for loading along the fiber axis. These values are valid for both tension and compression. Limits are 95 percent confidence limits.

	<u>No. of specimens</u>
S_{11} , GPa ⁻¹	0.01582 \pm 0.00031
S_{12} , GPa ⁻¹	-0.00420 \pm 0.00008
S_{22} , GPa ⁻¹	0.05238 \pm 0.00081
S_{66} , GPa ⁻¹	0.1174 \pm 0.0033

Alternatively, expressing this result in terms of the invariants of the compliance tensor, we obtained:

	<u>Minimum No.</u> <u>of specimens</u>
I_1 , GPa ⁻¹	0.0598 \pm 0.00093
I_2 , GPa ⁻¹	0.1342 \pm 0.0033
II_1 , GPa ⁻¹	0.01828 \pm 0.00045
II_2 , GPa ⁻¹	0.00510 \pm 0.00044

- c. Taken from results at 65 vol% fiber.

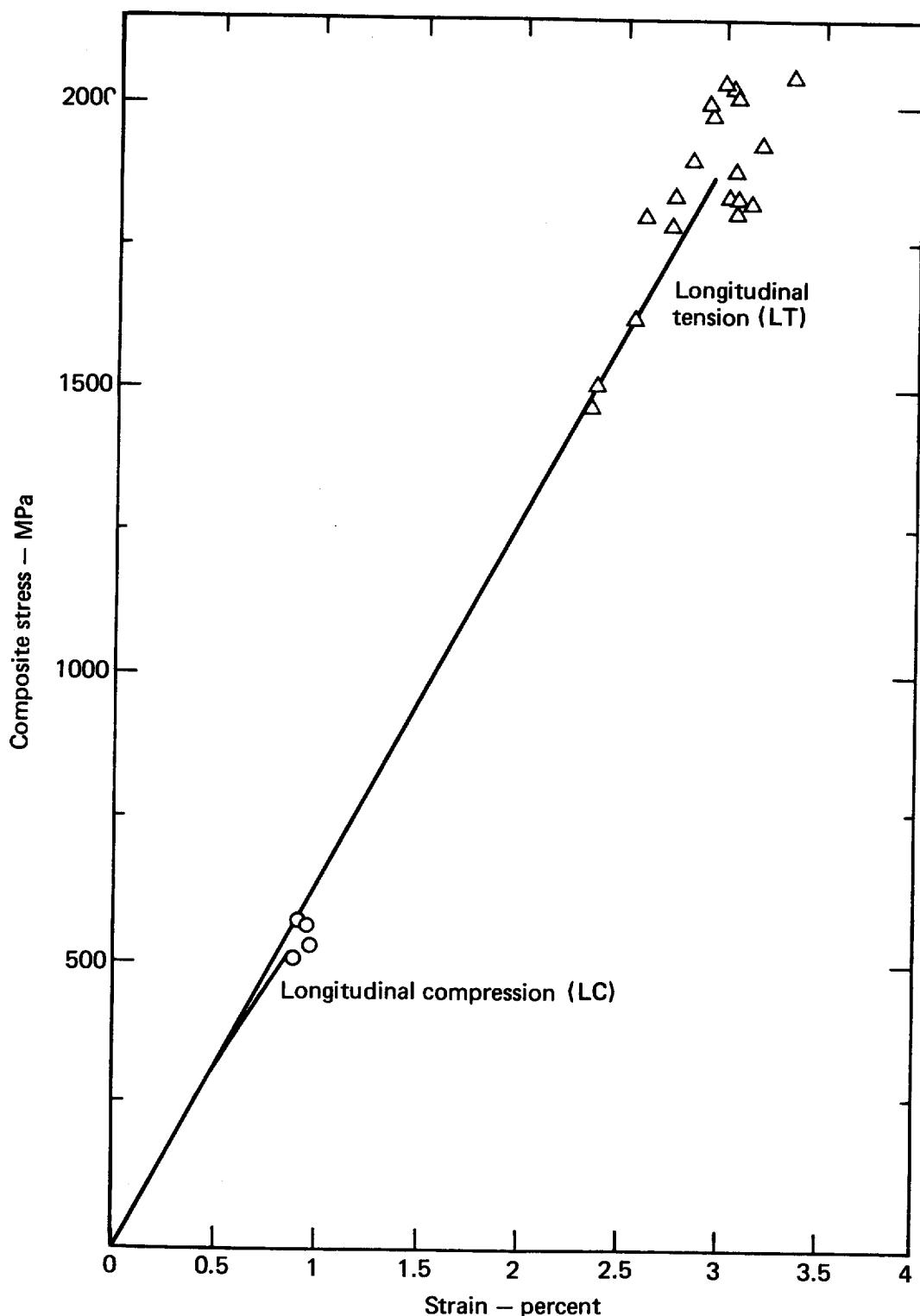


Fig. 28. Average longitudinal stress-strain, with individual failure points, for S-2 glass in DER 332-T403 epoxy matrix. Stress values are normalized to 70 vol% fiber. Actual vol% fiber: 41-64(LT), 63.4(LC); No. of specimens: elastic constants, 31, stress, 29(LT), 4(LC), strain, 5(LT), 4(LC).

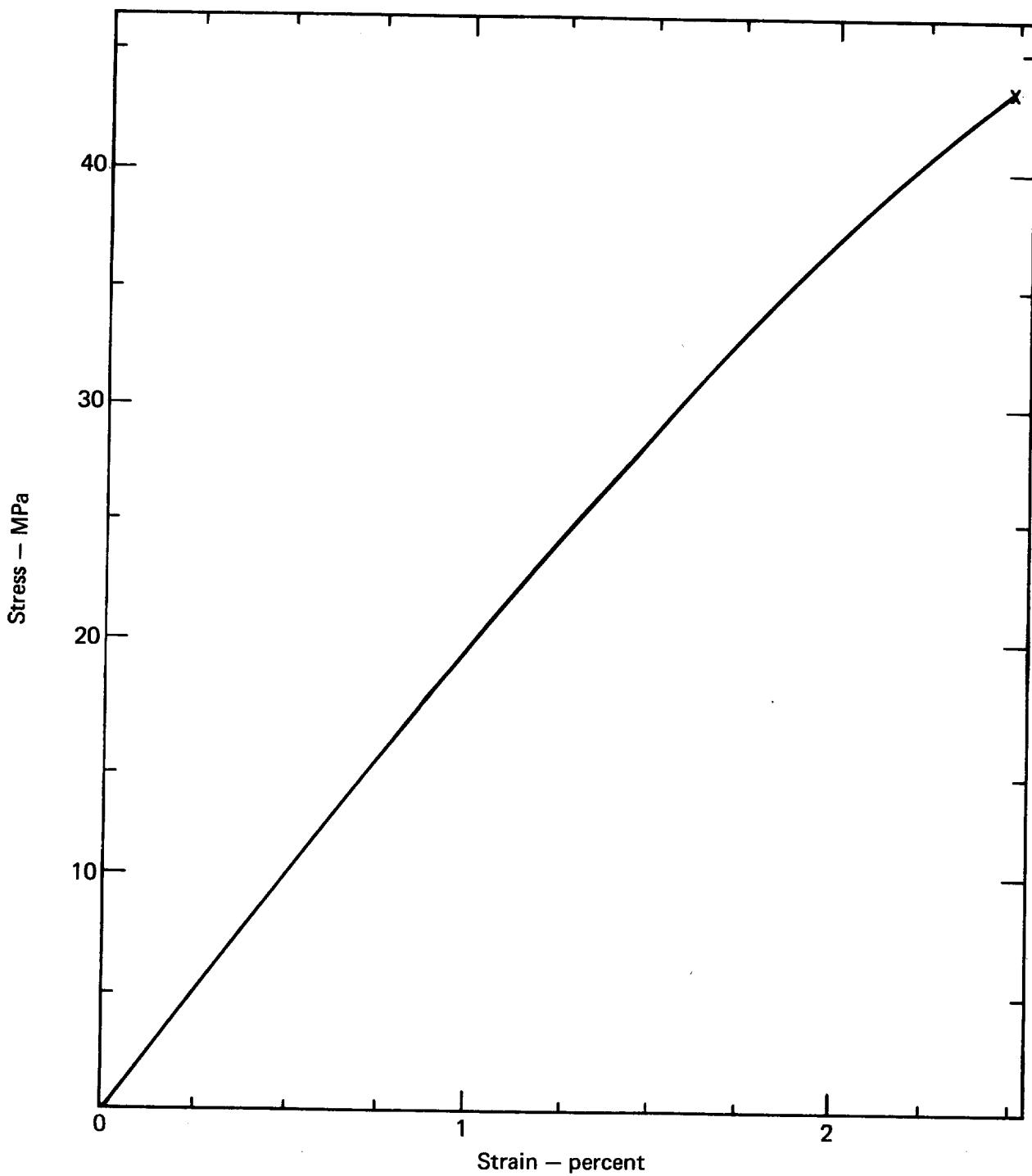


Fig. 29. Average transverse tensile stress-strain for S-2 glass (70 vol%) in DER 332-T403 epoxy matrix. Curve data are extrapolated from tests of 29 specimens, 44-68 vol% fiber. Compression behavior may be approximated by 65 vol% fiber results.

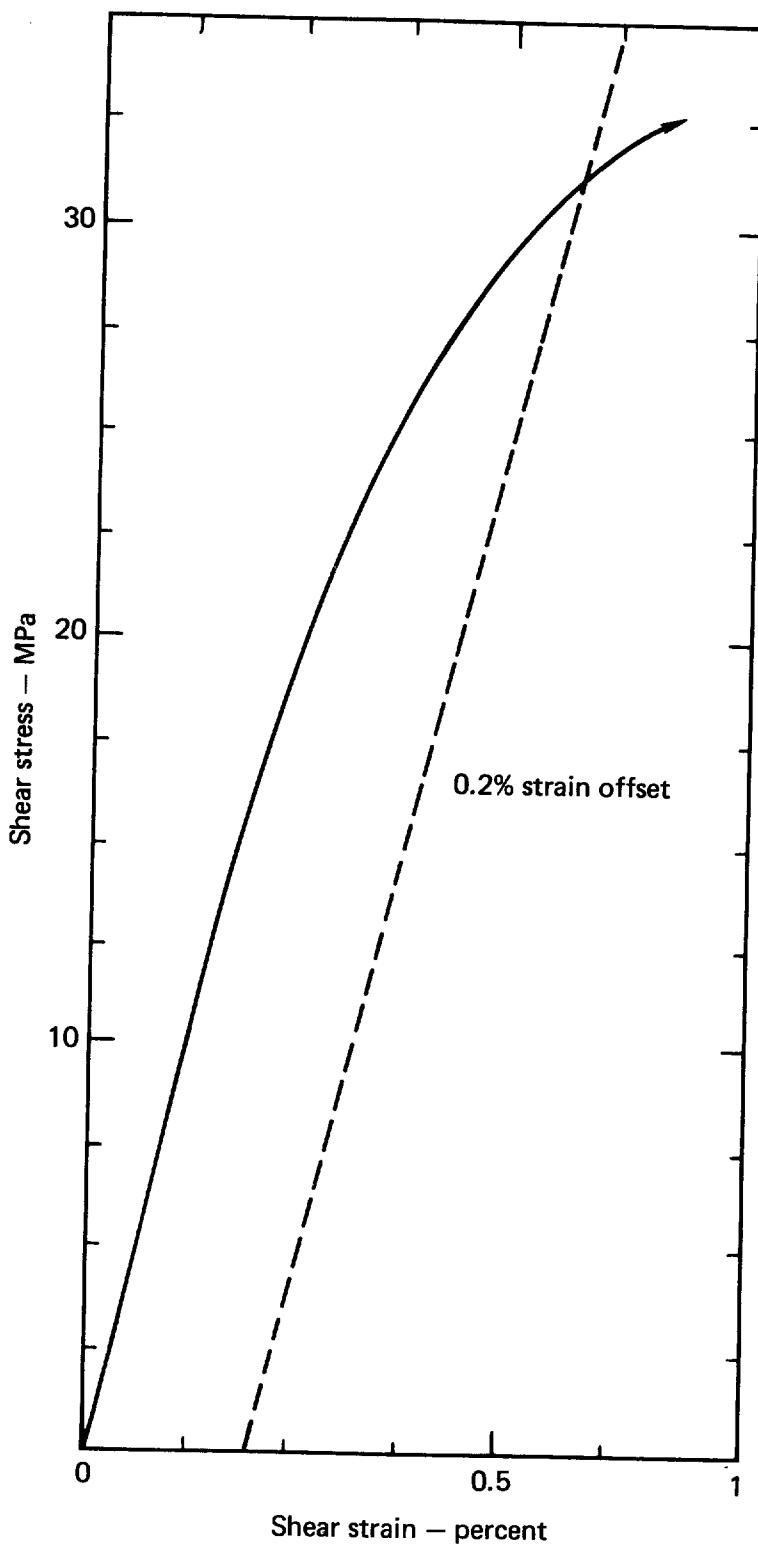


Fig. 30. Average shear stress-strain for S-2 glass (70 vol%) in DER 332-T403 epoxy matrix. Curve data are extrapolated from tests of 20 specimens, 62-69 vol% fiber.

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1. L. L. Clements, *Properties of Commercial Fibers used for Filament-Wound Composites*, Lawrence Livermore Laboratory, Livermore, Calif., UCID-17873, (1978).
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BD

APPENDIX: Calculation of Elastic Constants

The elastic constants given in the data sheets are calculated from the plane-stress compliance tensor for loading along the fiber axis. The compliance components are derived experimentally as the inverse of the slope of the appropriate uniaxial stress-strain curve. In contracted notation, the stress-strain relations of a general elastic material under a three-dimensional state of stress may be written as:

$$\epsilon_i = S_{ij} \sigma_j, \text{ where } S_{ij} \text{ is the compliance matrix.}$$

For a thin lamina subjected to in-plane loading, we assume a generalized plane-stress state. This implies:

$$\epsilon_i = S_{ij} \sigma_j, \text{ where } i, j = 1, 2, \text{ or } 6 \text{ only.}$$

For such a lamina loaded along a principal axis:

$$\begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{Bmatrix} \quad \left\{ \begin{matrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{matrix} \right\} \quad \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} \quad *$$

The complementary relationships such as $S_{22}(0^\circ) = S_{11}(90^\circ)$ and $S_{12}(0^\circ) = S_{12}(90^\circ)$ can now be used to give a complete matrix for 0° loading.

*Note that the relationship between contracted, expanded, and engineering notation is: $\epsilon_1 = \epsilon_{11} = \epsilon_x$, $\epsilon_2 = \epsilon_{22} = \epsilon_y$, $\epsilon_6 = 2\epsilon_{12} = \gamma_{xy}$ and $\sigma_1 = \sigma_{11} = \sigma_x$, $\sigma_2 = \sigma_{22} = \sigma_y$, $\sigma_6 = \sigma_{12} = \tau_{xy}$.

Once the complete 0° compliance tensor is determined, elastic moduli and Poisson's ratios are obtained from these components by the following formulae:

$$E_{11} = \frac{1}{S_{11}}, \quad E_{22} = \frac{1}{S_{22}}, \quad G_{12} = \frac{1}{S_{66}}, \quad v_{12} = -\frac{S_{12}}{S_{22}}, \quad v_{21} = -\frac{S_{12}}{S_{22}} .$$